

## Diatom Biostratigraphy of the Neogene Milky River Formation, Alaska Peninsula, Southwestern Alaska

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The Milky River Formation of the Alaska Peninsula, southwestern Alaska, contains more than 100 marine diatom and three silicoflagellate taxa in more than 50 samples from the 263-m-thick (863-foot-thick) Sandy Ridge stratigraphic section. Age-diagnostic diatoms include *Neodenticula kamtschatica*, *Thalassiosira oestrupii* and *Cosmiodiscus insignis*, whose co-occurrence characterizes the latest Miocene to early Pliocene subzone b of the North Pacific *Neodenticula kamtschatica* diatom Zone of Barron and Gladenkov (1995). The occurrence of additional biostratigraphically-important diatoms, including *Thalassiosira temperei* and *Thalassiosira latimarginata*, is the basis for refining the age of different parts of the formation. Diatoms occur directly within the shells of the bivalve *Astarte* and other marine mollusks of the Milky River Formation. The first appearance of *Astarte* in North Pacific stratigraphic sections signals the earliest opening of Bering Strait, because the genus otherwise dwelled only in the North Atlantic-Arctic region. Diatoms from the stratigraphically lowest *Astarte*-bearing horizon in the Milky River Formation indicate an age range of 5.5–5.4 Ma for the strait's earliest opening. Data on the age of Neogene diatom-bearing sediments resulting from this study also contribute to the stratigraphic framework of Alaska and to refined regional correlations.

Fossil diatoms occur widely in deep-sea and onshore stratigraphic sequences in the middle to high latitudes of the North Pacific and are the primary biostratigraphic tool for the precise dating and correlation of marine sediments in this region. The current high-resolution North Pacific Neogene diatom zonation includes numerous biohorizons based on datum levels, which have been directly correlated to the magnetostratigraphy of the late early Miocene to Quaternary (Barron 1980, 1992a; Koizumi and Tanimura 1985; Koizumi 1992; Barron and Gladenkov 1995; Yanagisawa and Akiba 1998). However, even though Cenozoic marine diatoms of different ages are well represented in sea floor sediments (Kanaya and Koizumi 1966; Jousé et al. 1969; Sancetta 1981a-b, 1982; Sancetta and Silvestri 1986) and deep-sea cores in the eastern part of the Bering Sea and the Gulf of Alaska (Schrader 1973; Barron and Gladenkov 1995), they are extremely rare or absent in onshore sequences of Alaska. As a result, it is often difficult to determine the precise ages and correlations of these sediments. A relatively diverse Neogene diatom flora has previously been studied only from the Pribilof Islands, southern Bering Sea, Alaska (Hanna 1919, 1970), and sparse remains of poorly preserved marine diatoms have also been reported from the Middleton Island section of the Yakataga Formation along the northeastern Gulf of Alaska margin (Plafker and Addicott 1976). Assigning precise ages to these floras has proved difficult, owing to

the absence of biostratigraphically significant taxa. The present study of diatoms from the Milky River Formation, including age-diagnostic species, is the first description of a Cenozoic diatom assemblage from the Alaska Peninsula, southwestern Alaska. These diatoms are present in stratigraphically well-controlled samples and are highly significant for age, regional correlations, and paleoenvironmental reconstruction of the Milky River Formation.

### PREVIOUS STUDIES, MATERIALS AND METHODS

Certain diatom species in the Milky River marine diatom flora have been the basis for documenting the earliest opening of Bering Strait (Marincovich and Gladenkov 1997, 1999, 2001; Gladenkov and Marincovich 1998, 1999). Part of the present diatom flora was first discovered within five mollusk shells from two stratigraphic levels in the Sandy Ridge stratigraphic section that were housed in the California Academy of Sciences, San Francisco. These samples had been collected from Sandy Ridge in the course of petroleum geological field work by Mobil Oil Company geologists in the 1970s. At that time, this sequence was assigned to the upper part of the Bear Lake Formation (Detterman et al. 1996). Initial study of the diatoms showed them to be characteristic of Subzone b of the North Pacific *Neodenticula kantschatica* diatom Zone of Barron and Gladenkov (1995), with an age range of 5.5–4.8 Ma based on correlations with the time scale of Berggren et al. (1995). Even though these diatoms and mollusks (*Astarte*) were the basis for dating the earliest opening of Bering Strait (Marincovich and Gladenkov 1999, 2001; Marincovich 2000), the precise location of these fossils in the Sandy Ridge stratigraphic section was unknown. In order to place these fossils within a stratigraphic, geological and paleontological context, field work at Sandy Ridge was conducted in August 1998 and July 1999 under the leadership of L. Marincovich, Jr. and supported by National Science Foundation grant OPP 9806461 (Marincovich et al. 2002; Gladenkov et al. 2002). This additional sampling at Sandy Ridge was critical to more precisely dating the first occurrence of Arctic-Atlantic mollusks within the North Pacific diatom biostratigraphic scheme, especially since diatoms were absent or extremely rare in the enclosing matrix but relatively abundant in the mollusk shells. Sampling the interiors of mollusk shells was done because in some cases fossil diatoms are present in fine sediment within shells and are thereby protected from abrasion and dissolution (Barron and Mahood 1993). Fine grained sediments containing diatoms might also be protected from winnowing by bottom currents if they are within molluscan shells.

A total of 56 samples for diatom analysis were collected during field work at the Sandy Ridge stratigraphic section (Figure 1). These strata had previously been assigned to the Bear Lake Formation (Detterman et al. 1996). However, in the course of field work it was discovered that the main part of these rocks contain, exclusively, late Miocene mollusks, in contrast to the early middle Miocene mollusks known from the Bear Lake Formation (Marincovich et al. 2002; Gladenkov et al. 2002). These strata were therefore reassigned to the Milky River Formation, which had been proposed by Galloway (1974) for volcanic and sedimentary rocks that overlies the Bear Lake Formation on the Alaska Peninsula. A profound angular unconformity separates these two formations at Sandy Ridge, with semi-isoclinally folded non-marine conglomerate, sandstone and coal beds of the lower middle Miocene Bear Lake Formation underlying subhorizontal shallow-marine sediments of the upper Miocene Milky River Formation. It is now clear that all previously studied marine diatoms and mollusks from this stratigraphic section came not from the upper part of the Bear Lake Formation, as supposed by Marincovich and Gladenkov (1997, 1999, 2001), but from the overlying Milky River Formation. The stratigraphic horizon with the first appearance of *Astarte*, which is the signal of an open Bering Strait, is 28 meters above the angular unconformity

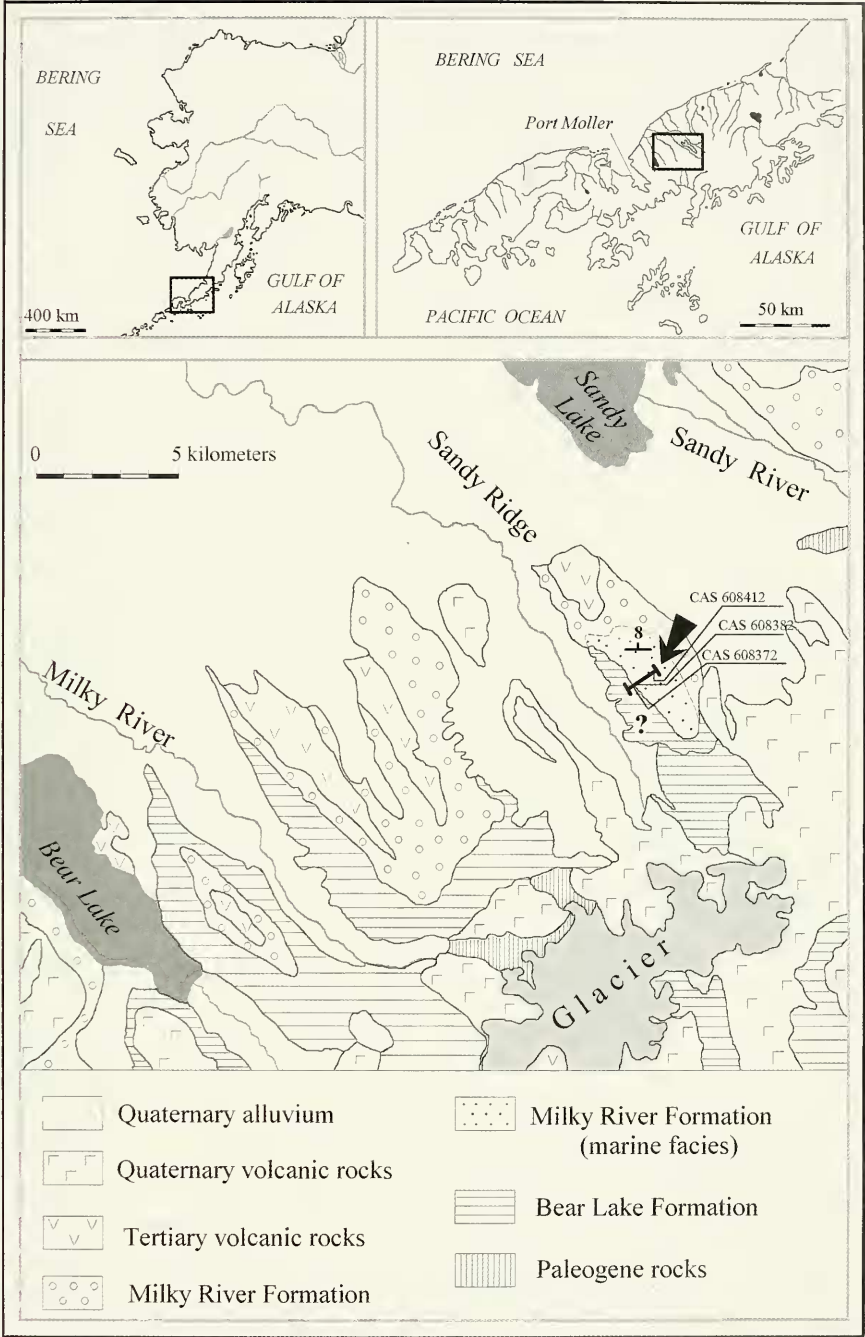


FIGURE 1. Location of the study area on the Alaska Peninsula and geological map of the Sandy Ridge area (modified after Detterman et al. 1996), with arrow showing the Sandy Ridge stratigraphic section of the Milky River Formation (after Gladenkov et al. 2002). Localities of the stratigraphically lowest (CAS 608372) and highest (CAS 608412) samples in the Sandy Ridge stratigraphic section yielding diatoms are shown. CAS 608382 indicates the locality of sample collected from the stratigraphically lowest *Astarte*-bearing horizon in the Milky River Formation.

and within the lower part of the Milky River Formation (Marincovich et al. 2002; Gladenkov et al. 2002). In the course of field work at Sandy Ridge, 52 samples for diatom analysis were collected from the 263-m-thick (863-ft-thick) section of the Milky River Formation and four samples were collected from the uppermost part of the underlying Bear Lake Formation (Figures 1–2; Table 1).

Due to the induration of the sediments and the low concentration of diatoms, the following procedure was used to process the samples. Samples were preliminary crushed and then placed in acetic acid for several days. The acid-treated material was then made pH-neutral by repeatedly filling and decanting the beakers with distilled water, allowing 3 hr or more for each rinse. The material was then processed by boiling it in a solution of water and sodium pyrophosphate ( $\text{Na}_4\text{P}_2\text{O}_7 \times 10\text{H}_2\text{O}$ ), followed by repeated washing with distilled water, and then a centrifuge (at 2500 rpm for 10 min) was used with heavy liquid (specific weight = 2.3) to separate a suspension fraction. To remove the heavy liquid, both the suspension and residue were again rinsed in distilled water. Finally, strewn slides were prepared by placing the material in a vial, adding distilled water, agitating the vial, and removing part of the upper suspension with a pipette. Strewn slides<sup>1</sup> were prepared by spreading the pipette suspension onto a cover slip (size 24×24 mm), drying on a hot plate, and mounting in Naphrax (index of refraction = 1.74). Slides prepared from both fractions obtained after centrifuging were studied as a control. The slides were examined in their entirety under a Jeneval (Zeiss) light microscope at 400×, with identifications routinely checked at 1000×. Whenever possible, all diatom taxa were counted up to a maximum of 200 specimens (other than *Chaetoceros* spores). *Chaetoceros* spores were tabulated separately while counting the other taxa. After counting, slides were scanned to record the presence of other diatom species missed among the first 200 specimens. When fewer than 200 diatom valves were encountered on a slide, all of the taxa were tabulated. Silicoflagellates, if present, were tabulated for the entire slide. The preservation of diatoms is listed as G (good), M (moderate), and P (poor) depending on the degree of destruction and dissolution of valves. The relative abundance is evaluated as A (abundant, more than 1500 diatom valves per slide), C (common, 400–1500 valves), F (few, 250–400 valves), and R (rare, 250–50 valves), and VR (very rare, less than 50 valves).

Numerical ages have been updated herein according to the geochronologic and geomagnetic polarity scales after Berggren et al. (1995). The correlation of geological epochs and periods also follows Berggren et al. (1995), with the exception of the Pliocene subepochs. The Pliocene epoch

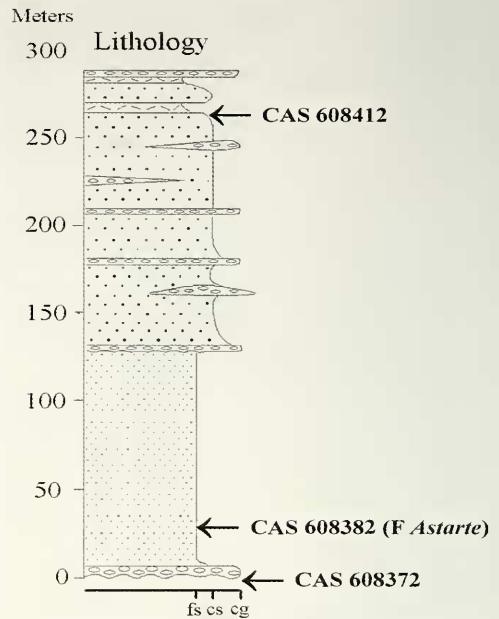


FIGURE 2. Generalized stratigraphic column of the Milky River Formation at the Sandy Ridge stratigraphic section (after Gladenkov et al. 2002)

The wavy line indicates an angular unconformity separating the Milky River Formation and the Bear Lake Formation. Arrows show stratigraphically lowest (CAS 608372) and highest (CAS 608412) samples levels possessing diatoms, and the sample level (CAS 608382) coinciding with the stratigraphically lowest Astarte-bearing horizon (F Astarte). Abbreviations used: fs—fine-grained sandstones, cs—coarse grained sandstones, cg—conglomerate.

<sup>1</sup>The original set of slides are in Gladenkov's laboratory in Moscow. A duplicate set of slides has been deposited in the Diatom Collection at the California Academy of Sciences.

is divided into early, middle, and late subepochs that are equivalent to the European Zanclean, Piacenzian, and Gelasian stages, respectively. As a result, the former late Pliocene is divided into middle and late subepochs, as was adopted at the 30th International Geological Congress (Beijing, China, 1996). The boundary between middle and late Pliocene is at 2.58 Ma coinciding with the top of Chron C2An. The North Pacific Neogene diatom zonation follows Barron and Gladenkov (1995) (Figure 3).

## RESULTS AND DISCUSSION

**OCCURRENCE OF BIOSTRATIGRAPHICALLY SIGNIFICANT TAXA.**— Three of 4 samples from the Bear Lake Formation are barren of siliceous microfossils. Rare diatoms representing only a few taxa were found only in sample CAS 608372 (1.5 m below the unconformity) (Figures 1–2). Determining a precise age for the poorly preserved assemblage in sample CAS 608372, from the uppermost part of the Bear Lake Formation at Sandy Ridge, has proven difficult owing to the absence of co-occurring, biostratigraphically significant taxa characteristic of the *Neodenticula kamtschatica* Zone or older diatom zones (Table 1). About 100 species and varieties of diatoms and three taxa of silicoflagellates were identified in the 52 samples examined from the 263-m-thick section of the Milky River Formation exposed above the unconformity at the Sandy Ridge stratigraphic section. Their occurrences are shown in Table 1. In addition, because of its importance, the richest diatom-bearing sample (CAS 60269-s) of five samples reported by us previously (Marincovich and Gladenkov 1999, 2001) is included in the occurrence chart here. Its stratigraphic position approximately coincides with that of sample CAS 608382 (about 28 m above the unconformity), which was collected from the horizon characterized by the first appearance of mollusks *Astarte* in the Milky River Formation. The Appendix gives taxonomic citations for the taxa encountered.

In general the diatom flora of the Milky River Formation consists of boreal and subarctic species typical of high to middle latitudes (Plates 1–7; Table 1; Appendix). The North Pacific diatom zonations of Akiba (1986), Koizumi (1992), Barron and Gladenkov (1995), and Yanagisawa and Akiba (1998) are most applicable to this study. A version of the Cenozoic diatom zonation proposed by Barron and Gladenkov (1995) for the North Pacific (Figure 3) is used here. In Figure 4 the stratigraphic ranges of selected diatoms are used to correlate micropaleontological assemblages from the Sandy Ridge section with diatom zones and subzones.

Overall, diatoms are rare to abundant and well preserved to poorly preserved throughout the

TABLE 1. Stratigraphic occurrences and relative abundances of selected diatoms from the Sandy Ridge stratigraphic section

Notes: Stratigraphic interval is in meters above the base of the Milky River Formation, which is marked by an angular unconformity at Sandy Ridge. The location of sample CAS 60269-s coincides approximately with that of sample CAS 608382, which was collected from the horizon containing the stratigraphically lowest occurrence of the bivalve mollusk *Astarte*. Sample CAS 608372 is from the uppermost part of the Bear Lake Formation at Sandy Ridge.

Preservation (G = good, M = moderate, P = poor) and relative abundance (A = abundant, C = common, F = few, R = rare, VR = very rare). Plus sign (+) indicate diatom specimens recorded after the count.

A total number of valves of all diatom taxa counted in each sample are shown. However, because of space limitations, only occurrences for stratigraphically important marine diatoms and taxa having a most importance for paleoenvironments are included in Table 1. Other taxa (primary nonmarine and benthic) were also tabulated, however they are not treated here. Identified taxa of silicoflagellates are also not included. Interested persons may contact the author for a complete chart of taxonomic occurrences in the Sandy Ridge stratigraphic section.

Partial boxes within the table indicate the first or/and last occurrences of the biostratigraphically most important species in the Milky River Formation at Sandy Ridge stratigraphic section.

Elevation above the unconformity (m)	263.0	246.0	246.0	237.4	222.2	207.9	188.7	172.8	155.5	147.2	146.6	139.9	139.9	134.1	133.2	121.3	114.6	103.0	96.6	95.1	94.8	
Sample #CAS-	608412	608411	608410	608409	608408	608407	608406	608405	608404	608403	608402	608401	608400	608399	608398	608397	608396	608395	608427	608426	608394	
Preservation	M	P	P	M	M	P	P	P	P	M	P	M	G	P	P	P	P	P	P	M	P	
Abundance	R	VR	R	VR	F	VR	VR	VR	R	R	VR	F	A	F	F	F	F	R	R	C-F	R	
<i>Actinocyclus curvatulus</i>					1				1			+	1	1							2	
<i>A. ochotensis</i>	1				+							+	1	1	1		+				+	
<i>A. octonarius</i>					1			1				+	1	1	+	+					1	1
<i>Actinocyclus</i> spp.					1			2				1	1									
<i>Actinoptychus senarius</i>					1			1				3	8	2	3	4	11				2	1
<i>A. splendens</i>												+	1	+	+			1				
<i>Adoneis pacifica</i>																						+
<i>Bacteriastrum varians</i>														+								
<i>Bacterosira fragilis</i>	2				9			1	4	1	10	5	13	9	11	17	1	1	20		2	
<i>Cladogramma dubium</i>					+							+		+	+				1			
<i>Coscinodiscus marginatus</i>	3	1			8			7	1	1	20	26	25	15	34	9	12	5	8		3	
<i>Cosmiodiscus insignis</i>					1			1	4	1	22	34	15	12	36	18	17	3	3		4	
<i>Cymatosira debyi</i>											1			1	2	1	1				2	
<i>Delphineis angustata</i> group					2				1		3	+	2	5	1	1					4	
<i>D. sachalinensis</i>					+							+	+			1	1				3	
<i>D. simonsenii</i>																						
<i>D. surirella</i>					+				1		1	+	1	+	2	1					3	
<i>Detonula confervacea</i>					+				1		1		+		+	1					2	
<i>Dictadia capreeolus</i>					+								1			+					+	
<i>Fragilariopsis cylindrus</i>																+					+	
<i>F. oceanica</i>																	+				+	
<i>Hyalodiscus obsoletus</i>					3						2	1		+	2						1	
<i>Hyalopyxis concava</i> + <i>Troctosira spinosa</i>	1	1			6			1	3	1	12	3	4	17	24	35	2				12	2
<i>Lithodesmium minusculum</i>												+	+									1
<i>Neodenticula kamschatcica</i>				1	+			1			+	+			1	1						3
<i>Nitzschia rolandii</i>																						
<i>Odoniella aurita</i>	1							1	1		1	1			1	1					2	
<i>Paralia sulcata</i>	1	1	1		18			3	16	2	3	34	58	37	38	44	45	28	7	15		4
<i>Porosira punctata</i>											1		+	+								
<i>Pseudopyxilla americana</i>					1								+									
<i>Pyxidicula zabelinae</i>	1	3	3	1	26			3	15	1		12	13	9	8	2	3	4	3	3	1	
<i>Rhaphoneis angularis</i>					1				1		+	1	1	1	1	2	2				1	1
<i>Rhizosolenia hebetata</i> group												+			1							
<i>Stephanogomia hanzawae</i>															1							+
<i>Thalassionema nitzschioides</i>	4	1	1		68			2	13	8	2	47	23	38	43	8	24	3	2	64	3	
<i>Thalassiosira antiqua</i>					+				1		1	1		1		1					8	1
<i>Thalassiosira</i> sp. cf. <i>T. convexa</i>																						
<i>T. dolmatovae</i>	2				2				2	1	9	8	7	7	2	7	2				2	3
<i>T. eccentrica</i>								1			1	+			+	1					4	1
<i>T. gravida</i>					+						1	+	1	4							1	
<i>T. hvalina</i>											+	+			1	1					1	
<i>T. jacksonii</i>																						
<i>T. jouseae</i>					7						1	1	3	2	1	2					6	1
<i>T. kryophilula</i>																					+	
<i>T. latinarginata</i>					1																+	
<i>T. leptopus</i>																						
<i>T. manifesta</i>									1													
<i>T. marjamica</i>																						
<i>T. nativa</i> + <i>T.</i> sp. cf. <i>nativa</i>			2	1	2					5		+	1		1	1					1	
<i>T. oestrupii</i>	1				2			1	1		1	1	1	1	+	1					1	1
<i>T. orientalis</i>					1							1	+								1	
<i>T. praeoestrupii</i>																						
<i>T. sheslukovae</i>					1						+	+	+	1	1						2	
<i>T. temperci</i>																						
<i>T. tertiaris</i>																					+	
<i>T. undulosa</i> + <i>Porosira glacialis</i>											1	4	+	+	+	2					2	
<i>Thalassiothrix longissima</i>					2						1	+	+	2	+	+					3	
<i>T. robusta</i>					8				1	2	4	3	8	10	1	5	1				9	1
Resting spores of <i>Chaetoceros</i>	1	4	3		25			1	8	2	1	19	8	6	23	3	25	3	2	53	2	
Total number of valves counted	87	30	77	44	200	34	18	22	132	64	17	200	200	200	200	200	200	109	65	200	66	



Milky River Formation at Sandy Ridge. The first occurrences of *Thalassiosira oestrupii*, *T. antiqua*, *T. jouseae*, *T. marujamica*, *T. sheshukovae*, *Neodenticula kamtschatica*, *Bacterosira fragilis*, *Detonula confervacea* and *Rhaphoneis angularis* are in sample CAS 617358 from the basal part of the Milky River Formation (0.9 m above the base). *Thalassiosira oestrupii* ranges to the top of the section in sample CAS 608412 (263.0 m). The last occurrences of *Neodenticula kamtschatica* and *Cosmiodiscus insignis* are below the stratigraphic top, in samples CAS 608410 (246.0 m) and CAS 608408 (222.2 m), respectively. The last consistent occurrence of *Cosmiodiscus insignis* is in sample CAS 608405 (172.8 m). *Lithodesmium minusculum* is present in the interval from sample CAS 608376 (3.4 m) to sample CAS 608401 (139.9 m). *Delphines simonsenii* occurs from sample CAS 608379 (8.8 m) to sample CAS 608392 (85.3 m), and *Nitzschia rolandii* from sample CAS 608382 (28.0 m) to sample 608425 (93.0 m). *Thalassiosira jacksonii* and *Thalassiosira* sp. cf. *T. convexa* range from sample CAS 608376 (3.4 m) to sample CAS 608425 (93.0 m), including sample CAS 608393 (88.4 m). *Thalassiosira teuperei* is present in samples CAS 608378 (5.5 m) and CAS 608382 (28.0 m), while sample CAS 60269-s (about 28.0 m) contains *Thalassiosira praeoestrupii*. Samples CAS 608426 (95.1 m) and CAS 608408 (222.2 m) yield *Thalassiosira latimarginata*, while *Thalassiosira tertiaria* was found in samples CAS 608426 and CAS 608400 (139.9 m).

**AGE OF THE DIATOM FLORA.**— As noted above, determining a precise age for the poorly preserved assemblage in sample CAS 608372, from the uppermost part of the Bear Lake at Sandy Ridge, has proven difficult owing to the absence of co-occurring, biostratigraphically significant taxa characteristic of any North Pacific diatom zone. The co-occurrence of *Thalassiosira oestrupii*, *Cosmiodiscus insignis* and *Neodenticula kamtschatica* in the Milky River Formation allows recognition of the latest Miocene to early Pliocene subzone b of the North Pacific *Neodenticula kamtschatica* Zone of Barron and Gladenkov (1995) in the Sandy Ridge stratigraphic section. The *Neodenticula kamtschatica* Zone is the interval from the first occurrence (FO) of *N. kamtschatica* to the FO of *N. koizumii* (Figure 3). This zone is divided into subzones a, b, and c by the FO of *Thalassiosira oestrupii* and the last occurrence (LO) of *Cosmiodiscus insignis*, following Barron (1980). Thus, based on the find of *Cosmiodiscus insignis* in sample CAS 608408 (222.2 m), most of the Milky River Formation at Sandy Ridge section can be correlated with subzone b of the *N. kamtschatica* Zone. The boundaries of the *N. kamtschatica* Zone and its subzones, based on diatom datum levels, are calibrated with the magnetostratigraphic record in the North Pacific (Barron and Gladenkov 1995). According to the geochronologic and chronostratigraphic scale of Berggren et al. (1995). Subzone b has an age range of 5.5 to 4.8 Ma. The Miocene/Pliocene boundary is currently placed at 5.32 Ma by Berggren et al. (1995). Diatoms from the uppermost part of the Milky River section, above sample CAS 608405 (172.8 m), however, are rare and generally exhibit poor preservation. So, it is uncertain whether *Cosmiodiscus insignis* has its true last occurrence in sample CAS 608408 (222.2 m), which is its final occurrence, or in sample CAS 608405 (172.8 m), which is its last consistent occurrence but where this species is represented by a single, possibly reworked specimen. On the other hand, the absence of *Cosmiodiscus insignis* above 222.2 m due to paleoecological changes cannot be excluded. Therefore, a tentative upper boundary of subzone b, marked by the LO of *Cosmiodiscus insignis* at level 172.8 m, is proposed for the Sandy Ridge section.

The occurrence of additional biostratigraphically important diatoms allows refining the age for the different parts of the stratigraphic section. Not all horizons in this section are characterized by the consistent occurrence of diatoms, including age-diagnostic marine taxa, but analysis of the species still is valuable. The most important species for biochronology in the lower part of Milky River Formation is *Thalassiosira teuperei* (Figure 4). The last occurrence of this species is a useful Neogene biohorizon marker in the North Pacific, including onshore sequences in Japan and



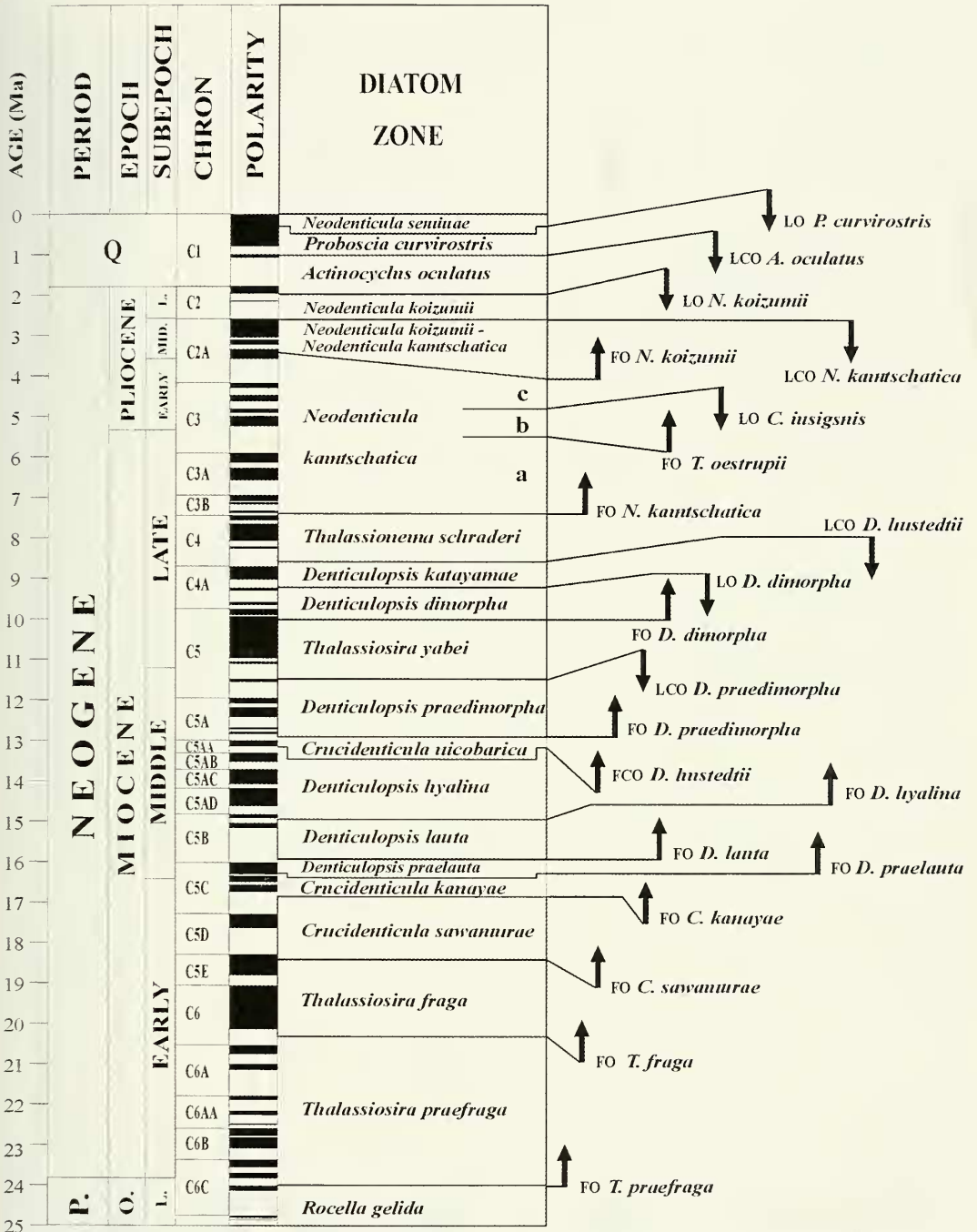


FIGURE 3. The North Pacific Neogene diatom zonation after Barron and Gladenkov (1995) correlated to the geomagnetic polarity time scale and chronostratigraphic subdivisions of Berggren et al. (1995) (see text for additional explanation). Abbreviations used: FO, first occurrence; LO, last occurrence; FCO, first common occurrence; LCO, last common occurrence; a-c, subzones; Q, Quaternary; P, Paleogene; O, Oligocene; L, late.



Kamchatka. It occurs within the interval corresponding to the lowermost part of subzone b of the *Neodenticula kamtschatica* diatom Zone (Barron 1980, 1992a; Akiba et al. 1982; Oreshkina 1985; Akiba 1986; Akiba and Yanagisawa 1986; Yanagisawa 1990, 1998). The most recent data, based on extrapolated sedimentation rates and occurrences in deep-sea cores, indicates that *Thalassiosira temperei* had its last occurrence at 5.4 Ma in the middle- to high-latitude North Pacific (Yanagisawa and Akiba 1998) (Figure 4). Therefore, the co-occurrence of *Thalassiosira temperei*, *T. oestrupii*, and *Cosmiodiscus insignis* indicates a narrow age interval of 5.5 to 5.4 Ma for the lower part of the Milky River Formation at Sandy Ridge.

The presence of secondary marker species, including *Delphines simonsenii*, *Bacterosira fragilis*, *Detonula confervacea*, and *Thalassiosira jouseae*, are useful for evaluating the lower age limit of the Milky River Formation at Sandy Ridge. According to Akiba (1986), the first occurrences of all of these species at DSDP Site 584 off northeastern Japan, are within the interval corresponding to subzone b of the *Neodenticula kamtschatica* Zone of Barron and Gladenkov (1995). More precisely, these species first occur within a narrow interval just above the FO of *Thalassiosira oestrupii*. The total occurrence of *Delphines simonsenii* is restricted to subzone b at DSDP Site 584 (Akiba 1986). These datum levels have not been directly correlated to magnetostratigraphy, but the presence of these species in the Sandy Ridge section supports a lower limit for the Milky River Formation of not more than 5.5 Ma.

As shown in Table 1, *Rhaphoneis angularis* is typical of diatom assemblages from the Milky River Formation. In the Harris Grade section, California, this species ranges from between the first occurrences of *Thalassiosira oestrupii* and *Thalassiosira praeoestrupii*, i.e. from about 5.3-5.4 Ma (Barron and Baldauf 1986; Dumont and Barron 1995). On the other hand, in sequences from the Oregon continental shelf *Rhaphoneis angularis* ranges from an older interval corresponding to the uppermost part of the *Thalassionema schraderi* Zone (Whiting and Schrader 1985). So, the datum from California may not apply in more northern regions such as Alaska.

In summary, diatoms imply an age range for lower 28 m of the Milky River Formation, below sample CAS 608382 (which has the last co-occurrence of *Thalassiosira temperei*, *T. oestrupii*, *Neodenticula kamtschatica*, and *Cosmiodiscus insignis*) of 5.5–5.4 Ma.

The most biochronologically important species in the upper part of Milky River Formation are *Thalassiosira latimarginata* and *Thalassiosira tertiaria*. As noted above, *T. latimarginata* is present in samples CAS 608426 (95.1 m) and CAS 608408 (222.2 m), and *T. tertiaria* in samples CAS 608426 and CAS 608400 (139.9 m). The FO of *T. latimarginata* has been calibrated with the magnetostratigraphic record of deep-sea cores in the subarctic North Pacific at about 5.1 Ma (Barron and Gladenkov 1995). The FO of *T. tertiaria* has been correlated with magnetostratigraphy in ODP

FIGURE 4. Published biostratigraphic ranges of selected diatom taxa present in the Sandy Ridge stratigraphic section (SRS), indicating a latest Miocene to early Pliocene age for the Milky River Formation (MRF).

Black triangle in parentheses indicates that *Thalassiosira* sp. cf. *T. convexa* is present in the Milky River Formation (see Appendix).

Key to published ranges: 1. Barron and Gladenkov (1995\*), ODP sites in the subarctic North Pacific. 2. Yanagisawa and Akiba (1998), DSDP Hole 438A, off northeastern Japan. 3. Barron (1980), DSDP sites, off northeastern Japan. 4. Barron (1992a\*), DSDP and ODP sites in the North Pacific. 5. Barron (1992b), California. 6. Oreshkina (1985; personal communication, 1998), DSDP Site 192, off northeastern Kamchatka. 7. Barron and Baldauf (1986), California. 8. Dumont and Barron (1995), California. 9. Whiting and Schrader (1985), the Oregon continental shelf. 10. Schrader (1973), DSDP sites in the Gulf of Alaska. 11. Akiba (1986), DSDP Site 584, off northeastern Japan. 12. Koizumi (1992\*), ODP sites in the Japan Sea. 13. Koizumi and Tanimura (1985\*), DSDP sites in the northwestern Pacific. Asterisks (\*) indicate a paleomagnetic calibration.

The North Pacific diatom zonation of Barron and Gladenkov (1995) for the last 8 myr correlated to the geomagnetic polarity time scale and chronostratigraphic subdivisions of Berggren et al. (1995).

Abbreviations used: Q, Quaternary; a-c, subzones; DSDP, Deep Sea Drilling Project; ODP, Ocean Drilling Program.

Site 884 in the western part of the subarctic North Pacific, where it has an age of 5.0 Ma (Barron and Gladenkov 1995). Thus, the presence of these species in the Milky River Formation indicates an age not older than 5.1–5.0 Ma for the horizons overlying the 95.1-m level.

*Lithodesmium minusculum* (occurring from 3.4 m to 139.9 m) could have served as an additional useful age marker for the upper portion of the section studied. The age range of the last occurrence of this species in California is 4.6–4.8 Ma (Barron 1992b; Dumont and Barron 1995). However, the presence of *Lithodesmium minusculum* is documented in younger horizons of the *Neodenticula koizumii*-*Neodenticula kamtschatica* Zone at DSDP Site 192, off northeastern Kamchatka (T. Oreshkina 1985, personal communication 1998). These data suggest that the datum from California may not apply in more northerly regions, such as Alaska.

**COMPARISON WITH THE DIATOM FLORA OF THE PRIBILOF ISLANDS.**— As noted in the Introduction, a relatively well-preserved and diverse fossil marine diatom flora from an onshore sequence in Alaska has previously been documented and studied only from the Pribilof Islands, Bering Sea (Hanna 1919, 1970). Overall, this diatom assemblage is comprised of relatively long-ranging forms with little or no precise age significance. In contrast to the flora from the Sandy Ridge section, this diatom assemblage lacks most of the biostratigraphically-important taxa typical of the Milky River Formation, such as *Neodenticula kamtschatica*, *Thalassiosira oestrupii*, *T. latimarginata*, *Bacterosira fragilis*, *Detonula confervacea*, *Thalassiosira jouseae*, and *Delphineis simonsenii*. However, both floras have a few species in common, including *Coscinodiscus insignis* and *Thalassiosira temperei* (referred to as *Cymatotheca weissflogii* by Hanna 1970). These latter species suggest that the flora from the Pribilof Islands is older than the one at Sandy Ridge and has an age older than 5.5 Ma. This conclusion is supported by data from L. Burckle and N. Opdyke, who studied diatoms and magnetostratigraphy from sequences in the Pribilof Islands (Burckle and Opdyke, unpublished data). Diatom-bearing sediments exposed in outcrops on St. Paul Island exhibit the normal polarity of Chron C3A (Burckle, personal communication 2002), which ranges in age from 6.57 Ma to 5.89 Ma (Berggren et al. 1995). This age range implies that the diatom flora from of the Pribilof Islands is possibly assignable to the older part of the North Pacific *Neodenticula kamtschatica* diatom Zone, which is Subzone a that has an age range of 7.4–5.5 Ma. The absence of the zonal species *Neodenticula kamtschatica* in the Pribilof Islands flora is possibly due to paleoecological exclusion. However, the absence of *Neodenticula kamtschatica* due to the possible difference of preparation methods, including the procedures of processing of samples, between Hanna (1970) and this study also cannot be excluded.

**DIATOM PALEOENVIRONMENTS.**— In general, the diatom flora from the Milky River Formation is composed by boreal and subarctic species typical of high to middle latitudes. Overall, the assemblages are dominated by marine neritic-planktic and sublittoral taxa (including *Paralia sulcata*, *Chaetoceros* spores and *Delphineis* spp.) that are accompanied by benthic and nonmarine forms, which implies deposition in productive shallow water (shallower than 100 m) of the Alaskan continental shelf (Sancetta 1981a-b; Sancetta and Silvestri 1986). The persistence and occasional-ly common occurrence of *Thalassionema nitzschioides* accompanied by oceanic planktic elements suggests incursions of transitional water from the outer shelf zone, where shelf and oceanic waters are incompletely mixed. The presence of *Fragilariopsis oceanica* and *F. cylindrus*, which commonly live near sea ice, as well as some marine arctoboreal species (*Bacterosira fragilis*, *Detonula confervacea*, *Porosira glacialis*, *Thalassiosira kryophila*, *T. hyalina*, *T. gravida*) imply periods of bloom associated with melting ice near the continental margin of southwestern Alaska. Sparse occurrences of subtropical or transitional planktonic taxa such as *Thalassiosira leptopus*, *T. lineata*, *T. temperei*, *T. oestrupii*, *Bacteriastrum varians*, *Auliscus* and *Azpeitia* spp. suggest possible episodes of relatively warmer conditions.

## SUMMARY

The 263-m-thick stratigraphic section of the Milky River Formation at Sandy Ridge contains Neogene marine diatom assemblages of different preservation and abundance. A total of about 100 species and varieties of diatoms were identified in the samples examined. The presence of the marker species *Neodenticula kamtschatica*, *Cosmiodiscus insignis*, and *Thalassiosira oestrupii* throughout the section allows recognition of the latest Miocene to early Pliocene subzone b of the *Neodenticula kamtschatica* Zone of Barron and Gladenkov (1995), which has an age range of 5.5 to 4.8 Ma. Additional age-diagnostic diatoms, including *Thalassiosira temperei* and *T. latimarginata*, allow refining the age for the basal part of the Milky River Formation to 5.5 Ma to 5.4 Ma, and to 5.1 Ma to 4.8 Ma for the upper part of the formation at Sandy Ridge. This information, from stratigraphically well-controlled samples, is the basis for dating mollusks that occur directly with the diatoms, including the biogeographically important bivalve *Astarte*. Diatoms in the stratigraphically lowest *Astarte*-bearing horizon at Sandy Ridge have an age range of 5.5–5.4 Ma, which is the basis for dating the earliest opening of Bering Strait (Marincovich and Gladenkov 1999, 2001; Marincovich et al. 2002; Gladenkov et al. 2002).

Both the dominant and common elements of the Milky River Formation flora imply deposition on a productive continental shelf, with some incursions of transitional waters from the outer shelf zone. The presence of species living with sea ice, along with marine arctoboreal species, suggests periods of bloom associated with the melting of ice near the continental margin of southwestern Alaska. Sparse occurrences of subtropical or transitional planktonic taxa suggest transient warmer conditions.

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## LITERATURE CITED

- AKIBA, F. 1986. Middle Miocene to Quaternary diatom biostratigraphy in the Nankai Trough and Japan Trench, and modified lower Miocene through Quaternary diatom zones for the middle-to-high latitudes of the North Pacific. Pages 393–481 in H. Kagami, D.E. Karig, W.T. Coulbourn, et al., eds., *Initial Reports, Deep Sea Drilling Project 87*. U.S. Govt. Printing Office, Washington, D.C.
- AKIBA, F. AND Y. YANAGISAWA. 1986. Taxonomy, morphology and phylogeny of the Neogene diatom zonal marker species in the middle-to-high latitudes of the North Pacific. Pages 483–554 in H. Kagami, D.E. Karig, W.T. Coulbourn, et al., eds., *Initial Reports, Deep Sea Drilling Project 87*. U.S. Govt. Printing Office, Washington, D.C.
- AKIBA, F., Y. YANAGISAWA Y., AND T. ISHII. 1982. Neogene diatom biostratigraphy of the Matsushima area and its environs, Miyagi Prefecture, Northeast Japan. *Bulletin of the Geological Survey of Japan* 33 (5):215–239. (in Japanese with English abstract)
- ANDREWS, G.W. 1977. Morphology and stratigraphic significance of *Delphineis*, a new marine diatom genus.

*Beihefte zur Nova Hedwigia* 54: 243–260.

- ANDREWS, G.W. 1980. Revision of the diatom genus *Delphineis* and morphology of *Delphineis surirella* (Ehrenberg) G.W. Andrews, n. comb. Pages 81–92 in R. Ross, ed., *Proceedings of the 6th International Diatom Symposium*. Koeltz Scientific Books, Koenigstein.
- ANDREWS, G.W. 1988. Evolutionary trends in the marine diatom genus *Delphineis* G.W. Andrews. Pages 197–206 in F.E. Round, ed., *Proceedings of the 9th International Diatom Symposium*. Biopress, Bristol & Koeltz Scientific Books, Koenigstein.
- ANDREWS, G.W. AND P. RIVERA. 1987. Morphology and evolutionary significance of *Adoneis pacifica* gen. et sp. nov. (Fragilariaceae, Bacillariophyta), a marine araphid diatom from Chile. *Diatom Research* 2:1–14.
- BARRON, J.A. 1975. Late Miocene-early Pliocene marine diatoms from southern California. *Palaeontographica* 151(B):97–170, pls. 1–15.
- BARRON, J.A. 1980. Lower Miocene to Quaternary diatom biostratigraphy of Leg 57, off Northeastern Japan, Deep Sea Drilling Project. Pages 641–685 in E. Honza et al., eds., *Initial Reports, Deep Sea Drilling Project* 56, 57. U.S. Govt. Printing Office, Washington, D.C.
- BARRON, J.A. 1985. Miocene to Holocene planktic diatoms. Pages 641–691 in H.M. Bolli, J.B. Saunders, and K. Perch-Nielsen, eds., *Plankton Stratigraphy*. Cambridge University Press, Cambridge, UK.
- BARRON, J.A. 1992a. Neogene diatom datum levels in the Equatorial and North Pacific. Pages 413–425 in K. Ishizaki and T. Saito, eds., *Centenary of Japanese Micropaleontology*. Terra Scientific Publishing Company, Tokyo.
- BARRON, J.A. 1992b. Paleooceanographic and tectonic controls on the Pliocene diatom record of California. Pages 25–41 in R. Tsuchi and J.C. Ingle, Jr., eds., *Pacific Neogene — Environment, Evolution, and Events*. University of Tokyo Press, Tokyo.
- BARRON, J.A. AND J.G. BALDAUF. 1986. Diatom stratigraphy of the lower Pliocene part of the Sisquoc Formation, Harris Grade section, California. *Micropaleontology* 32:357–371.
- BARRON, J.A. AND A.Y. GLADENKOV. 1995. Early Miocene to Pleistocene diatom stratigraphy of Leg 145. Pages 3–19 in D.K. Rea, I. A. Basov, D. W. Scholl, and J. F. Allan, eds., *Proceedings of the Ocean Drilling Program, Scientific Results* 145. College Station, TX.
- BARRON, J.A. AND A.D. MAHOOD. 1993. Exceptionally well-preserved early Oligocene diatoms from glacial sediments of Prydz Bay, East Antarctica. *Micropaleontology* 39:29–45.
- BERGGREN, W.A., D.V. KENT, C.C. SWISHER III, AND M.-P. AUBRY. 1995. A revised Cenozoic geochronology and chronostratigraphy. *SEPM Special Publication* 54:129–212.
- BODÉN, P. 1993. Taxonomy and stratigraphic occurrence of *Thalassiosira tetraoestrupii* sp. nov. and related species in upper Miocene and lower Pliocene sediments from the Norwegian Sea, North Atlantic and North West Pacific. *Terra Nova* 5:61–75.
- DEETERMAN, R.L., J.E. CASE, J.W. MILLER, F.H. WILSON, AND M.E. YOUNT. 1996. Stratigraphic framework of the Alaska Peninsula. *U.S. Geological Survey Bulletin* 1969-A. 74 pp.
- DONAHUE, J.G. 1970. Pleistocene diatoms as climatic indicators in North Pacific sediments. *Geological Society of America Memoir* 126:121–138.
- DUMONT, M.P., J.G. BALDAUF, AND J.A. BARRON. 1986. *Thalassiosira praeoestrupii* — a new diatom species for recognizing the Miocene/Pliocene Epoch boundary in coastal California. *Micropaleontology* 32:372–377.
- DUMONT, M.P., AND J.A. BARRON. 1995. Diatom biochronology of the Sisquoc Formation in the Santa Maria Basin, California, and its paleoceanographic and tectonic implication. *U.S. Geological Survey Bulletin* 1995: K1–K17.
- DZINORIDZE, R.N. AND I.V. MAKAROVA. 1988. Genera *Porosira* Jörg., *Bacterosira* Gran, *Detonula* Schütt, *Landeria* Cl. Pages 86–89, pls. 59–60 in S.I. Gleser, I.V. Makarova, A.I. Moisseeva, and V.A. Nikolaev, eds., *The Diatoms of the USSR (Fossil and Recent)* II(1). Nauka Publishers, Leningrad. (in Russian)
- FRYXELL, G.A. AND G.R. HASLE. 1979. The genus *Thalassiosira*: *T. trifulta* sp. nova and other species with tricolunar supports on strutted processes. *Beihefte zur Nova Hedwigia* 64:13–32, 7 pls.
- GALLOWAY, W.E. 1974. Deposition and diagenetic alternation of sandstone in northeast Pacific arc-related basins — Implication for graywacke genesis. *Geological Society of America Bulletin* 83:379–390.
- GLADENKOV, A.Y. AND L. MARINCOVICH, JR. 1998. New data on the first opening of Bering Strait, based on

- finds of Neogene marine diatoms in the Bear Lake Formation, SW Alaska. *Abstracts 6th International Conference on Paleoceanography*, Lisbon, Portugal, p. 115.
- GLADENKOV, A.Y. AND L. MARINCOVICH, JR. 1999. The earliest age of the Bering Strait's first opening in the Neogene: paleontological evidence. European Union of Geosciences, March 28th-April 1st, 1999, Strasbourg, France. *Journal of Conference Abstracts* 4(1):179-180.
- GLADENKOV, A.Y., A.E. OLEINIK, L. MARINCOVICH, JR., AND K.B. BARINOV. 2002. A refined age for the earliest opening of Bering Strait. *Palaeogeography, Palaeoclimatology, Palaeoecology* 183:321-328.
- GLADENKOV, Y.B., K.B. BARINOV, A.E. BASILIAN, S.I. BORDUNOV, G.M. BRATSEVA, E.V. ZYRYANOV, N.P. KURALENKO, D.I. VITUKHIN, T.V. ORESHKINA, S.S. GANZEI, S.I. KIYASHKO, AND V.M. TRUBIKHIN. 1992. *Detailed Division of the Neogene of Kamchatka*. Moscow, Nauka Publishers. 208 pp. (in Russian)
- HANNA, G D. 1919. Geological notes on the Pribilof Islands, Alaska, with an account of the fossil diatoms. *American Journal of Science* 48:216-224.
- HANNA, G D. 1970. Fossil diatoms from the Pribilof Islands, Bering Sea, Alaska. *Proceedings of the California Academy of Sciences*, ser. 4, 37(5):167-234.
- HARWOOD, D.M. AND T. MARUYAMA. 1992. Middle Eocene to Pleistocene diatom biostratigraphy of Southern Ocean sediments from the Kerguelen Plateau, Leg 120. Pages 683-733 in S. W. Wise, Jr., R. Schlich, et al., eds., *Proceedings of the Ocean Drilling Program, Scientific Results* 120. College Station, TX.
- HASLE, G.R. 1993. Nomenclatural notes on marine planktonic diatoms. The family Bacillariaceae. *Beihfte zur Nova Hedwigia* 106:315-321.
- HASLE, G.R., P.A. SIMS, AND E.E. SYVERTSEN. 1988. Two recent *Stellarima* species: *S. microtrias* and *S. stellaris* (Bacillariophyceae). *Botanica Marina* 31:195-206.
- JORDAN, R.W., R. LIGOWSKI, E.-M. NÖTHIG, AND J. PRIDDLE. 1991. The diatom genus *Proboscia* in Antarctic waters. *Diatom Research* 6:63-78.
- JORDAN, R.W. AND J. PRIDDLE. 1991. Fossil members of the diatom genus *Proboscia*. *Diatom Research* 6: 55-61.
- JOUSÉ, A.P. 1961. Miocene and Pliocene marine diatoms from the Far East. *Botanicheskie Materialy Otdela Sporovykh Rastenii, Botanicheskii Institute, Akad. Nauk SSSR* 14:59-70, pls. 1-3. Akad. Nauk SSSR Publishers, Moscow-Leningrad. (in Russian)
- JOUSÉ, A.P. 1968. New species of diatoms from bottom sediments of the Pacific and the Okhotsk Sea. *Novitates Systematicae Plantarum Non Vascularium*:12-21. Nauka Publishers, Leningrad. (in Russian)
- JOUSÉ, A.P., V.V. MUKHINA, AND O.G. KOZLOVA. 1969. Diatoms and silicoflagellates in the surface layer of sediments from the Pacific Ocean. Pages 7-47 in P. L. Bezrukov, ed., *The Pacific Ocean. Vol. 7: Microflora and microfauna in the modern sediments of the Pacific Ocean*. Nauka Publishers, Moscow. (in Russian)
- KANAYA, T. 1959. Miocene diatom assemblages from the Onnagawa Formation and their distribution in the correlative formations in Northeast Japan. *Science Reports of the Tohoku University, Second Ser. (Geol.)* 30:1-130, 11 pls.
- KANAYA, T. AND I. KOIZUMI. 1966. Interpretation of diatom thanatocoenoses from the North Pacific applied to a study of core V20-130 (Studies of a deep-sea core V20-130. Part IV). *Science Reports of the Tohoku University, Second Ser. (Geol.)* 37 (2): 89-130.
- KOIZUMI, I. 1973. The late Cenozoic diatoms of Sites 183-193, Leg 19, Deep Sea Drilling Project. Pages 805-855 in J.S. Creager, D.W. Scholl, et al., eds., *Initial Reports, Deep Sea Drilling Project* 19. U. S. Govt. Printing Office, Washington, D.C.
- KOIZUMI, I. 1975. Neogene diatoms from the western margin of the Pacific Ocean, Leg 31, Deep Sea Drilling Project. Pages 779-819 in D.E. Karig, J.C. Ingle, Jr., et al., eds., *Initial Reports, Deep Sea Drilling Project* 31. U.S. Govt. Printing Office, , Washington, D.C.
- KOIZUMI, I. 1980. Neogene diatoms from the Emperor Seamount Chain, Leg 55, Deep Sea Drilling Project. Pages 387-407 in E.D. Jackson, I. Koizumi, et al., eds., *Initial Reports, Deep Sea Drilling Project* 55. U.S. Govt. Printing Office, Washington, D.C.
- KOIZUMI, I. 1992. Diatom biostratigraphy of the Japan Sea: Leg 127. Pages 249-289 in K. Pisciotto, J.C. Ingle, Jr., M. von Breyman, and J.A. Barron, eds., *Proceedings of the Ocean Drilling Program, Scientific Results* 127/128 (Pt. 1). College Station, TX.
- KOIZUMI, I. AND Y. TANIMURA. 1985. Neogene diatom biostratigraphy of the middle latitude western North

- Pacific, Deep Sea Drilling Project Leg 86. Pages 269–300 in G.R. Heath, L.H. Burckle, et al., eds.; *Initial Reports, Deep Sea Drilling Project 86*. U.S. Govt. Printing Office, Washington, D.C.
- LOHMAN, K.E. 1938. Pliocene diatoms from the Kettleman Hills, California. *U.S. Geological Survey Professional Paper* (189-C):81–102, pls. 20–23.
- MAKAROVA, I.V. 1988a. New combinations of taxa from the late Miocene-early Pliocene diatom floras of Sakhalin. *Botanicheskii Zhurnal* 73(8):1183–1186, pls. 1–2. (in Russian)
- MAKAROVA, I.V. 1988b. Diatoms of the USSR seas: genus *Thalassiosira* Cl. Nauka Publishers, Leningrad. 117 pp. (in Russian)
- MAKAROVA, I.V. 1988c. Genus *Thalassiosira* Cl. Pages 58–82, pls. 37–57 in S. I. Gleser, I.V. Makarova, A.I. Moisseeva, and V.A. Nikolaev, eds., *The Diatoms of the USSR (Fossil and Recent)* II(1). Nauka Publishers, Leningrad. (in Russian)
- MAKAROVA, I.V. 1989. New genus of centric diatoms. *Novitates Systematicae Plantarum Non Vascularum* 26:34–35, pls. 1–2. Nauka Publishers, Leningrad. (in Russian)
- MAKAROVA, I.V. AND A.I. MOISSEVA. 1986. New species of genus *Pyxidicula* (Bacillariophyta). *Botanicheskii Zhurnal* 71(2):244–245, pls. 1–2. (in Russian)
- MARINCOVICH, L., JR. 2000. Central American paleoceanography controlled Pliocene Arctic molluscan migration. *Geology* 28:551–554.
- MARINCOVICH, L., JR., K.B. BARINOV, AND A.E. OLEINIK. 2002. The *Astarte* (Bivalvia: Astartidae) that document the earliest opening of Bering Strait. *Journal of Paleontology* 76:239–245.
- MARINCOVICH, L., JR. AND A.Y. GLADENKOV. 1997. New paleontological information about the first opening of Bering Strait. *Program and Abstracts, Beringian Paleoenvironments Workshop*, Florissant, Colorado, pp. 103–104.
- MARINCOVICH, L., JR. AND A.Y. GLADENKOV. 1999. Evidence for an early opening of the Bering Strait. *Nature* 397:149–151.
- MARINCOVICH, L., JR. AND A.Y. GLADENKOV. 2001. New evidence for the age of Bering Strait. *Quaternary Science Reviews* 20:329–335.
- MUKHINA, V.V. 1965. New species of diatoms from bottom sediments of the Equatorial Pacific. *Novitates Systematicae Plantarum Non Vascularum*: 22–25. Nauka Publishers, Moscow-Leningrad. (in Russian)
- ORESHKINA, T.V. 1985. Diatom assemblages and stratigraphy of the upper Cenozoic off Kamchatka region of the Pacific Ocean. *Izvestiya Akademii Nauk SSSR, Geology Series* 5:60–73. (in Russian)
- PERCH-NIELSEN, K. 1985. Silicoflagellates. Pages 811–846 in H.M. Bolli, J.B. Saunders, and K. Perch-Nielsen, eds., *Plankton Stratigraphy*. Cambridge University Press, Cambridge, UK.
- PLAFKER, G. AND W.O. ADDICOTT. 1976. Glaciomarine deposits of Miocene through Holocene age in the Yakataga Formation along the Gulf of Alaska margin, Alaska. Pages Q1–Q22 in T.P. Miller, ed., *Recent and Ancient Sedimentary Environments in Alaska*. Alaska Geological Society Symposium Proceedings.
- SANCETTA, C. 1981a. Diatoms as hydrographic tracers: example from Bering Sea sediments. *Science* 211:279–281.
- SANCETTA, C. 1981b. Oceanographic and ecologic significance of diatoms in surface sediments of the Bering and Okhotsk seas. *Deep Sea Research* 28A(8):789–817.
- SANCETTA, C. 1982. Distribution of diatom species in surface sediments of the Bering and Okhotsk seas. *Micropaleontology* 28:221–257.
- SANCETTA, C. AND S. SILVESTRI. 1986. Pliocene-Pleistocene evolution of the North Pacific Ocean-atmosphere system, interpreted from fossil diatoms. *Paleoceanography* 1:163–180.
- SCHRADER, H.-J. 1973. Cenozoic diatoms from the Northeast Pacific, Leg 18. Pages 673–797 in L.D. Kulm, R. von Huene, et al., eds., *Initial Reports, Deep Sea Drilling Project 18*. U.S. Govt. Printing Office, Washington, D.C.
- SCHRADER, H.-J. AND J. FENNER. 1976. Norwegian Sea Cenozoic diatom biostratigraphy and taxonomy. Pages 921–1099 in M. Talwani, G. Udintsev, et al., eds.; *Initial Reports, Deep Sea Drilling Project 38*. U.S. Govt. Printing Office, Washington, D.C.
- SHESHUKOVA-PORETSKAYA, V.S. 1964. New and rare marine diatoms from the Neogene of Sakhalin and Kamchatka. *Novitates Systematicae Plantarum Non Vascularum*: 69–77. Nauka Publishers, Moscow-Leningrad. (in Russian)



- SHESHUKOVA-PORETSKAYA, V.S. 1967. *Neogene Marine Diatoms of Sakhalin and Kamchatka*. Leningrad State University Press, Leningrad. 432 pp. (in Russian)
- VOLOBUEVA, V.I., B.V. BELAYA, L.M. DOLMATOVA, A.V. GREVTSEV, P.S. MINYUK, V.E. NARKHINOVA, T.P. POLOVOVA, AND O.A. SHIRAYA. 1992. *Key Section of Marine Neogene of Northest Asia in Karaginsky Island*. Part II (Systematic part). SVKNII, Far East Branch of Russian Academy of Sciences, Magadan. 167 pp. (in Russian)
- WHITING, M.C. AND H. SCHRADER. 1985. Late Miocene to Early Pliocene marine diatom and silicoflagellate floras from the Oregon coast and continental shelf. *Micropaleontology* 31:249–270.
- WORNARDT, W.W., JR. 1967. Miocene and Pliocene marine diatoms from California. *California Academy of Sciences Occasional Papers* (63):1–108.
- YANAGISAWA, Y. 1990. Diatom biostratigraphy of the Neogene Sendai Group, northeast Honshu, Japan. *Bulletin of the Geological Survey of Japan* 41(1):1–25. (in Japanese with English abstract)
- YANAGISAWA, Y. 1998. Diatom biostratigraphy of the Neogene Tatsunokuchi Formation in the western Kitakami City, Iwate Prefecture, Japan. *Research Report Iwate Prefectural Museum* 14:29–36. (in Japanese with English abstract)
- YANAGISAWA, Y. AND F. AKIBA. 1990. Taxonomy and phylogeny of the three marine diatom genera, *Crucidentacula*, *Denticulopsis* and *Neodenticula*. *Bulletin of the Geological Survey of Japan* 41(5):197–301.
- YANAGISAWA, Y. AND F. AKIBA. 1998. Refined Neogene diatom biostratigraphy for the northwest Pacific around Japan with an introduction of code numbers for selected diatom biohorizons. *Journal of the Geological Society of Japan* 104(6):395–414.
- YANAGISAWA, Y., K. NAKAMURA, Y. SUZUKI, K. SAWAMURA, F. YOSHIDA, Y. TANAKA, Y. HONDA, AND M. TANAHASHI. 1989. Tertiary biostratigraphy and subsurface geology of the Futaba district, Joban Coalfield, northeast Japan. *Bulletin of the Geological Survey of Japan* 40(8):405–467. (in Japanese with English abstract)

## APPENDIX

### Taxonomic Notes and References to Good Figures

Taxonomic references to marine diatom and silicoflagellate taxa from the Milky River Formation, including those illustrated on Plates 1–7, are listed below. In general, only references to good figures are listed following a semicolon. Thus, with few exceptions, the reader should look to these references for the original citation of the taxon. Important synonyms and brief remarks are included.

In most cases, only generic distinctions were made for nonmarine diatoms encountered in the Milky River Formation samples. This group includes *Achnanthes* Bory, *Auophora* Ehrenberg ex Kützing, *Asteriouella* Hassal (tabulated together with *Tabellaria* Ehrenberg ex Kützing), *Aulacosira* Thwaites, *Cyclotella* Kützing ex Brebisson, *Cymbella* Agardh, *Dimerogramma* Ralfs, *Diatoma* De Candolle, *Eunotia* Ehrenberg, *Fragilaria* Lyngbye, *Gouphouena* Agardh, *Gyrosigma* Hassal, *Melosira* Agardh, *Meridon* Agardh, *Navicula* Bory, *Nitzschia* Hassal, *Pinnularia* Ehrenberg, *Surirella* Turpin, *Syuedra* Ehrenberg, *Tetracyclus* Ralfs, and *Tryblionella* Smith.

### Marine Diatoms

- Actinocyclus curvatulus* Janisch; Koizumi, 1973, pl. 1, figs. 1–6; Sancetta, 1982, pl. 1, figs. 1–3. Synonyms: *Actinocyclus divinus* (Grunow) Hustedt; *Coscinodiscus curvatulus* Grunow; *Coscinodiscus divinus* Grunow. (Plate 5, Figs. 11–12)
- Actinocyclus ochotensis* Jousé, 1968: pp. 17–18, pl. 2, figs. 2–5; Donahue, 1970, pl. 1, figs. a–b, d; Koizumi, 1973, pl. 2, figs. 3, 6–7; Sancetta, 1982, pl. 1, figs. 4–6. (Plate 5, Fig. 9)
- Actinocyclus octonarius* Ehrenberg; Wornardt, 1967, fig. 49. **Synonym:** *Actinocyclus ehrenbergii* Ralfs. (Plate 5, Fig. 5)

- Actinocyclus* Ehrenberg spp. **Remarks:** Some species of *Actinocyclus* have been not identified precisely. They have not been described or tabulated specifically here.
- Actinoptychus senarius* (Ehrenberg) Ehrenberg; Kanaya, 1959, pl. 7, fig. 17; Hanna, 1970, figs. 38–39; Sancetta, 1982, pl. 1, fig. 7; Akiba, 1986, pl. 29, fig. 2. **Synonym:** *Actinoptychus undulatus* (Bailey) Ralfs. (Plate 5, Fig. 8)
- Actinoptychus splendens* (Shadbolt) Ralfs; Sheshukova-Poretskaya, 1967, pl. 29, fig. 1; Hanna, 1970, figs. 25–26, 40, 44. (Plate 5, Fig. 1)
- Actinoptychus vulgaris* Schumann; Sheshukova-Poretskaya, 1967, pl. 28, figs. 2a–d; Sancetta, 1982, pl. 1, fig. 8; Akiba, 1986, pl. 29, fig. 1.
- Adoneis pacifica* Andrews et Rivera, 1987: pp. 2, 9, figs. 1–26. (Plate 1, Fig. 2)
- Arachnoidiscus* Bailey ex Ehrenberg spp. **Remarks:** Only scarce fragments of valves with the typical structure of *Arachnoidiscus* were observed. No attempt has been made to subdivide this group.
- Aulacodiscus* Ehrenberg spp. **Remarks:** No specific generic distinctions were made for rare specimens of *Aulacodiscus* and their fragments found in the material studied.
- Auliscus* sp. cf. *A. grunowii* Schmidt. **Remarks:** Only rare fragments of valves have been found. However, their structure resembles that of specimens illustrated by Wornardt (1967, figs. 92–94).
- Azpeitia* Peragallo spp. **Remarks:** The rare specimens observed here are similar in part to *Azpeitia nodulifera* (Schmidt) Fryxell et Sims and *Azpeitia tabularis* (Grunow) Fryxell et Sims, but they differ to some extent from these species by a character of valves structure.
- Bacteriarctum varians* Lauder; Barron, 1975, pl. 4, fig. 8. (Plate 2, Figs. 8–9)
- Bacterosira fragilis* (Gran) Gran; Sheshukova-Poretskaya, 1967, pl. 33, figs. 2a–b; Schrader, 1973, pl. 16, fig. 7; Sancetta, 1982, pl. 2, figs. 1–4; Akiba, 1986, pl. 4, figs. 1–4; Dzinoridze and Makarova, 1988, pl. 60, figs. 7–12. (Plate 3, Fig. 19; Plate 4, Fig. 18)
- Chaetoceros cinctus* Gran (spore); Sheshukova-Poretskaya, 1967, pl. 33, fig. 9. **Remarks:** Because of the similarity of *Chaetoceros cinctus* and *Chaetoceros incurvus* spores, they have been combined and counted together.
- Chaetoceros furcellatus* Bailey (spore); Sheshukova-Poretskaya, 1967, pl. 33, fig. 8; Sancetta, 1982, pl. 2, figs. 7, 9.
- Chaetoceros incurvus* Bailey (spore); Sheshukova-Poretskaya, 1967, pl. 33, fig. 10. **Remarks:** See Remarks for *Chaetoceros cinctus*.
- Chaetoceros septentrionales* Oestrup (spore); Sancetta, 1982, pl. 2, fig. 8.
- Chaetoceros subsecundus* (Grunow) Hustedt (spore); Sancetta, 1982, pl. 2, figs. 5–6. **Synonym:** *Chaetoceros diadema* (Ehrenberg) Gran.
- Cladogramma dubium* Lohman; Sheshukova-Poretskaya, 1967, pl. 24, figs. 6 a–b, pl. 29 figs. 4 a–c; Schrader, 1973, pl. 13, figs. 17–18, 21; Barron, 1975, pl. 5, fig. 10. (Plate 7, Figs. 3, 6)
- Cocconeis antiqua* Tempère et Brun; Hanna, 1970, fig. 48; Barron, 1975, pl. 5, fig. 11
- Cocconeis californica* Grunow; Sheshukova-Poretskaya, 1967, pl. 43, fig. 11; Yanagisawa et al., 1989, pl. 6, fig. 13.
- Cocconeis costata* Gregory; Sheshukova-Poretskaya, 1967, pl. 44, figs. 4 a–c; Barron, 1975, pl. 5, fig. 12; Sancetta, 1982, pl. 6, figs. 6–7.
- Cocconeis placentula* Ehrenberg; Barron, 1975, pl. 5, fig. 17.
- Cocconeis pribiloefformis* Hanna, 1970: p. 184, fig. 34.
- Cocconeis scutellum* Ehrenberg; Sheshukova-Poretskaya, 1967, pl. 44, fig. 7; Barron, 1975, pl. 5, fig. 19.
- Cocconeis vitrea* Brun; Sheshukova-Poretskaya, 1967, pl. 45, figs. 3a–c; Wornardt, 1967, figs. 183–184; Barron, 1975, pl. 5, fig. 23.
- Coscinodiscus asteromphalus* Ehrenberg; Sheshukova-Poretskaya, 1967, pl. 21, fig. 2; Wornardt, 1967, figs. 14–18; Schrader and Fenner, 1976, pl. 34, figs. 2–3.
- Coscinodiscus marginatus* Ehrenberg; Kanaya, 1959, pl. 4, figs. 4–6; Wornardt, 1967, figs. 27–28; Hanna, 1970, figs. 1–2; Barron, 1975, pl. 7, fig. 1; Akiba, 1986, pl. 1, figs. 1–4. (Plate 2, Figs. 4–5)
- Coscinodiscus oculus-iridis* Ehrenberg; Kanaya, 1959, pl. 4, fig. 7; Sheshukova-Poretskaya, 1967, pl. 21, fig. 1; Wornardt, 1967, figs. 34–35; Hanna, 1970, fig. 18; Barron, 1975, pl. 7, fig. 9; Sancetta, 1982, pl. 2, fig. 11.
- Coscinodiscus* Ehrenberg spp. **Remarks:** Rare fragments of different *Coscinodiscus* having indistinct charac-

ters for identification were assigned to this category.

*Cosmiodiscus insignis* Jousé, 1961: pp. 67–68, pl. 2, fig. 8; Sheshukova-Poretskaya, 1967, pl. 25, figs. 2 a–c; Hanna, 1970, figs. 9–11, 31, 32; Koizumi, 1973, pl. 4, figs. 7–11; Barron, 1980, pl. 4, fig. 1; Barron, 1985, fig. 9.9; Akiba, 1986, pl. 17, fig. 1. **Synonym:** *Thalassiosira insigna* (Jousé) Harwood et Maruyama sensu Barron and Gladenkov (1995). **Remarks:** Harwood and Maruyama (1992) transferred this taxon from *Cosmiodiscus* to *Thalassiosira* and proposed the new combination *Thalassiosira insigna* (Jousé) Harwood et Maruyama, based on observations of Antarctic forms bearing a central structure (dimple or bubble). Following Harwood and Maruyama (1992), in some cases this new combination has also been used for North Pacific forms (Barron and Gladenkov 1995; Marinovich and Gladenkov 1999, 2001; and others). However, recently, specimens of *Cosmiodiscus insignis* collected by G. D. Hanna from the Pribilof Islands were studied with a SEM by E. Fourtanier (Fourtanier, personal communication, 2001), who observed that the non-areolate center of the valve does not possess a central process, and that a ring of labiate processes is located on the boundary between the mantle and valve face. I also observed the same features when studying specimens of this taxon from the Milky River Formation with a SEM at the California Academy of Sciences in 2001. These observations indicate that this North Pacific taxon cannot be included in *Thalassiosira*, and that perhaps forms from the North Pacific and Antarctic regions belong to different taxa. Further study of the Antarctic forms under a SEM should clarify their taxonomic position. (**Plate 4, Fig. 16; Plate 6, Figs. 2–3, 5**)

*Cosmiodiscus intersectus* (Brun) Jousé, 1961: p. 68, pl. 2, figs. 9–10; Sheshukova-Poretskaya, 1967, pl. 25, figs. 1 a–b; Koizumi, 1973, pl. 4, figs. 12–13.

*Cymatosira debyi* Tempère et Brun; Sheshukova-Poretskaya, 1967, pl. 40, fig. 7, pl. 41, fig. 6; Akiba, 1986, pl. 19, figs. 19–20; Yanagisawa et al. 1989, pl. 5, fig. 31. (**Plate 3, Figs. 3–4; Plate 4, Fig. 8**)

*Delphineis angustata* (Pantocsek) Andrews group. **Remarks:** Specimens of *Delphineis* range from elliptical to elongate with rounded apices, and resemble *Delphineis angustata* (Pantocsek) Andrews, 1977, *Delphineis ischaboensis* (Grunow) Andrews, 1988, and *Delphineis karstenii* (Boden) Fryxell et Miller have been placed in this group in part following the example of *Delphineis* cf. *angustata* of Akiba (1986). (**Plate 4, Figs. 3–6, 10–11**)

*Delphineis sachalinensis* (Sheshukova) Barron et Baldauf, 1986: p. 363. **Synonym:** *Rhaphoneis sachalinensis* Sheshukova; Sheshukova-Poretskaya, 1967, p. 242, pl. 42, fig. 2. (**Plate 4, Fig. 13**)

*Delphineis simonsenii* (Mertz) Akiba, 1986: p. 439, pl. 20, figs. 12–13. (**Plate 5, Figs. 6–7**)

*Delphineis snirella* (Ehrenberg) Andrews, 1980: pp. 83–85; pl. 1, figs. 1–5, pl. 2, figs. 6–7; Akiba, 1986, pl. 20, figs. 2–3.

*Detonula confervacea* (Cleve) Gran; Dzinoridze and Makarova, 1988, p. 88, pl. 60, figs. 14–15, text figs. 6.1–6.3. **Synonym:** *Melosira albicans* Sheshukova, 1964; Sheshukova-Poretskaya, 1964, p. 69, 71, text figs. 1–2, pl. 1, fig. 3; 1967, pl. 10, figs. 2a–b, pl. 11, figs. 1a–b; Akiba, 1986, pl. 4, figs. 11–12; Yanagisawa et al., 1989, pl. 3, fig. 7. (**Plate 1, Fig. 9; Plate 5, Fig. 10**)

*Dicladia capreolus* Ehrenberg; Kanaya, 1959, pl. 11, figs. 1–2; Sheshukova-Poretskaya, 1967, pl. 34, figs. 1a–c. **Synonyms:** *Dicladia capreola* Ehrenberg; Hanna, 1970, fig. 63; *Dicladia pylea* Hanna et Grant; *Chaetoceros dicladia* Castracane. (**Plate 2, Figs. 2–3**)

*Diploneis smithii* (Brebisson) Cleve; Barron, 1975, pl. 8, fig. 17; Sancetta, 1982, pl. 6, fig. 21.

*Fragilariopsis cylindrus* (Grunow) Krieger; Koizumi, 1973, pl. 7, figs. 1–2; Hasle, 1993, p. 316. **Synonyms:** *Nitzschia cylindrus* (Grunow) Hasle; Koizumi, 1975, pl. 1, fig. 49; *Nitzschia cylindra* (Grunow) Hasle; Sancetta, 1982, pl. 3, figs. 6–7. (**Plate 3, Figs. 13–15**)

*Fragilariopsis oceanica* (Cleve) Hasle; Hasle, 1993, p. 317; **Synonym:** *Nitzschia grnmowii* Hasle; Sancetta, 1982, pl. 3, figs. 8–10; Akiba, 1986, pl. 24, figs. 19–21. (**Plate 3, Fig. 16–17**)

*Grammatophora* Ehrenberg spp. **Remarks:** Observed specimens resemble *G. angulosa* Ehrenberg and *G. arcuata* Ehrenberg and occur very sporadically.

*Hercotheca mamillaris* Ehrenberg; Barron, 1975, pl. 9, fig. 13.

*Hyalodiscus obsoletus* Sheshukova, 1964; Sheshukova-Poretskaya, 1964, p. 71, pl. 1, fig. 1; 1967, pl. 12, fig. 2; Akiba, 1986, pl. 29, fig. 15; Yanagisawa et al., 1989, pl. 3, fig. 12. (**Plate 1, Fig. 11**)

*Hyalopyxis concava* (Sheshukova) Makarova, 1989: p. 35, pl. 1, figs. 1–7, pl. 2, figs. 1–6. **Synonym:** *Trochosira concava* Sheshukova; Sheshukova-Poretskaya, 1967, p. 138, pl. 11, figs. 7a–b, pl. 13, fig. 3.

**Remarks:** Specimens of *Hyalopyxis concava* were tabulated together with specimens of *Trochosira spinosa* Kitton. (**Plate 3, Fig. 21–22**)

*Liradiscus ellipticus* Greville; Barron, 1975, pl. 9, fig. 19.

*Lithodesmium minusculum* Grunow; Warnardt, 1967, fig. 132; Schrader, 1973, pl. 12, figs. 15, 17; Barron, 1975, pl. 10, fig. 4; Oreshkina, 1985, pl. 3, fig. 15. (**Plate 7, Figs. 7, 11**)

*Navicula glacialis* Cleve; Sheshukova-Poretskaya, 1967, pl. 46, fig. 8.

*Neodenticula kantschatica* (Zabelina) Akiba et Yanagisawa, 1986: pp. 490–491, pl. 21, figs. 7–21, pl. 22, figs. 1–12; Akiba, 1986, pl. 25, figs. 7–27; Yanagisawa and Akiba, 1990, pl. 7, figs. 27–37. **Synonyms:** *Denticula kantschatica* Zabelina; Sheshukova-Poretskaya, 1967, pl. 47, figs. 9a–b, pl. 48, figs. 4a–d; Koizumi, 1973, pl. 5, figs. 14–17; Schrader, 1973, pl. 2, figs. 1–13; Koizumi, 1975, pl. 1, figs. 13–20; Barron, 1980, pl. 1, figs. 5–8; *Denticulopsis kantschatica* (Zabelina) Simonsen; Barron, 1985, fig. 13.16; Oreshkina, 1985, pl. 1, figs. 16–20; Whiting and Schrader, 1985, pl. 6, figs. 15–16, 18–20. (**Plate 5, Figs. 2–4; Plate 6, Fig. 4**)

*Nitzschia extincta* Kozyrenko et Sheshukova group. **Remarks:** Specimens having a similarity in shape and structure to *Nitzschia extincta* Kozyrenko et Sheshukova (*in* Sheshukova-Poretskaya, 1967, pp. 303–304, pl. 47, fig. 12) have been placed in this group.

*Nitzschia rolandii* Schrader; Akiba and Yanagisawa, 1986, pl. 21, figs. 1–6; Akiba, 1986, pl. 25, figs. 1–6; Yanagisawa and Akiba, 1990, pl. 7, figs. 17–26. (**Plate 3, Fig. 20**)

*Odontella aurita* (Lyngbye) Agardh; Sancetta, 1982, pl. 3, figs. 11–12; Akiba, 1986, pl. 17, figs. 2–3. (**Plate 2, Figs. 7, 10**)

*Opephora schwartzii* (Grunow) Petit; Warnardt, 1967, figs. 161–165; Barron, 1975, pl. 11, fig. 10.

*Paralia sulcata* (Ehrenberg) Cleve; Sancetta, 1982, pl. 3, figs. 13–15; Akiba, 1986, pl. 29, figs. 4–5. (**Plate 7, Figs. 12–13**)

*Pleurosigma* Smith spp. **Remarks:** No specific generic distinctions were made for rare specimens of *Pleurosigma* and their fragments found in the material studied.

*Porosira glacialis* (Grunow) Jørgensen; Koizumi, 1973, pl. 4, figs. 15–18; Barron, 1980, pl. 6, fig. 13; Dzinoridze and Makarova, 1988, pl. 60, figs. 1–6. **Remarks:** Specimens of *Porosira glacialis* were counted together with specimens of *Thalassiosira undulosa* (Mann) Sheshukova. (**Plate 7, Fig. 5**)

*Porosira punctata* (Jousé) Makarova, 1988: Makarova, 1988a, p. 1184, pl. 1, figs. 1–16; Dzinoridze and Makarova, 1988, pl. 59, figs. 1–10. **Synonym:** *Thalassiosira punctata* Jousé, 1961: p. 64, pl. 1, figs. 7–8, pl. 3, fig. 3; Sheshukova-Poretskaya, 1967, pl. 14, fig. 10, pl. 17, figs. 1a–b; Hanna, 1970, figs. 5–6; Koizumi, 1973, pl. 8, figs. 7–9; Schrader and Fenner, 1976, pl. 19, fig. 10; Barron, 1980, pl. 6, fig. 3; Akiba, 1986, pl. 9, figs. 5–6. (**Plate 2, Fig. 1; Plate 6, Fig. 12**)

*Proboscia alata* (Brightwell) Sundström; Jordan et al., 1991, figs. 1–9; **Synonym:** *Rhizosolenia alata* Brightwell; Schrader, 1973, pl. 10, fig. 12; Koizumi, 1975, pl. 1, fig. 38; Akiba, 1986, pl. 18, fig. 6.

*Proboscia barboi* (Brun) Jordan et Priddle, 1991: p. 56, figs. 1–2; **Synonyms:** *Rhizosolenia barboi* (Brun) Tempère et Peragallo; Schrader, 1973, pl. 24, figs. 4, 7; Barron, 1980, pl. 2, fig. 17; Barron, 1985, fig. 4.5; Akiba and Yanagisawa, 1986, pl. 42, figs. 3–5, 7, 10–11, pl. 44, figs. 1–8; *Rhizosolenia curvirostris* var. *inermis* Jousé; Donahue, 1970, pl. 1, figs. b–c; Koizumi, 1973, pl. 5, figs. 32–33.

*Pseudopyxilla americana* (Ehrenberg) Forti; Sheshukova-Poretskaya, 1967, pl. 39, figs. 2a–b; Schrader, 1973, pl. 10, fig. 22; Barron, 1975, pl. 11, fig. 12. (**Plate 7, Fig. 4**)

*Pseudopyxilla* Forti sp. **Remarks:** Only scarce fragments of *Pseudopyxilla* having some similarity to *Pseudopyxilla rossica* (Pantoscsek) Forti have been observed.

*Pyxidicula zabelinae* (Jousé) Makarova et Moisseeva; Makarova and Moisseeva, 1986, p. 244–245, pl. 1, figs. 1–15, pl. 2, figs. 1–15. **Synonyms:** *Thalassiosira zabelinae* Jousé, 1961: p. 66–67, pl. 2, figs. 1–7; Sheshukova-Poretskaya, 1967, pl. 16, figs. 2 a–d; *Thalassiosira usatschevii* Jousé, 1961: pp. 64, 66, pl. 1, fig. 10; Sheshukova-Poretskaya, 1967, pl. 15, figs. 3 a–d. (**Plate 1, Figs. 13, 15–16**)

*Rhabdonema japonicum* Tempère et Brun; Hanna, 1970, figs. 92–95; Schrader, 1973, pl. 12, fig. 10.

*Rhaphoneis amphiceros* Ehrenberg; Sheshukova-Poretskaya, 1967, pl. 41, fig. 9; Schrader, 1973, pl. 25, figs. 2–3; Whiting and Schrader, 1985, pl. 6, figs. 4–5; Akiba, 1986, pl. 20, fig. 19.

*Rhaphoneis angularis* Lohman, 1938: pp. 92–93, pl. 22, figs. 6–8; Schrader, 1973, pl. 26, figs. 9–10; Whiting and Schrader, 1985, pl. 6, figs. 22–24; Yanagisawa et al., 1989, pl. 5, fig. 38. **Synonym:** *Rhaphoneis amph-*

- iceros* var. *angularis* (Lohman) Wornardt, 1967: p. 78, figs. 169–170. (**Plate 4, Figs. 1–2, 7; Plate 6, Figs. 6, 10**)
- Rhizosolenia hebetata* (Bailey) Gran group. **Remarks:** All scarce specimens having a similarity with *Rhizosolenia hebetata* f. *hiemalis* Gran (Akiba, 1986, pl. 17, figs. 10–11, pl. 18, figs. 9–10) and *Rhizosolenia hebetata* f. *semispina* (Hensen) Gran (Akiba, 1986, pl. 18, fig. 8) were placed in this group. (**Plate 4, Fig. 12**)
- Rhizosolenia setigera* Brightwell; Akiba, 1986, pl. 18, fig. 5.
- Rhizosolenia styliformis* Brightwell; Sancetta, 1982, pl. 4, figs. 7–8; Akiba, 1986, 18, fig. 4.
- Stellarina microtrias* (Ehrenberg) Hasle et Sims; Hasle et al., 1988, figs. 1–25. **Synonym:** *Coscinodiscus symbolophorus* Grunow; Sheshukova-Poretskaya, 1967, pl. 22, figs. 3 a–e; Akiba, 1986, pl. 2, fig. 1.
- Stephanogonia hanzawae* Kanaya, 1959: pp. 118–119, pl. 11, figs. 3–7; Schrader and Fenner, 1976, pl. 12, figs. 10, 12, pl. 13, figs. 5, 7–8; Akiba et al., 1982, pl. 2, fig. 36. **Synonym:** *Pterotheca kittoniana* var. *kamtschatica* Gaponov; Sheshukova-Poretskaya, 1967, pl. 39, figs. 3a–f. (**Plate 1, Fig. 14**)
- Stephanopyxis turris* (Greville et Arnott) Ralfs; Kanaya, 1959, pl. 2, figs. 5–7; Koizumi, 1973, pl. 6, figs. 13–16; Schrader, 1973, pl. 15, figs. 1–7; Sancetta, 1982, pl. 4, figs. 9–10.
- Stephanopyxis* (Ehrenberg) Ehrenberg spp. **Remarks:** All scarce specimens not referable to *Stephanopyxis turris* were assigned to this category.
- Thalassionema nitzschioides* (Grunow) H. et M. Peragallo; Sancetta, 1982, pl. 4, figs. 11–13; Akiba, 1986, pl. 21, fig. 11. **Remarks:** No attempt was made to separate varieties of this species. (**Plate 3, Figs. 9–10**)
- Thalassiosira antiqua* (Grunow) Cleve-Euler; Sheshukova-Poretskaya, 1967, pl. 14, figs. 3a–b; Schrader, 1973, pl. 11, fig. 25, pl. 25, fig. 25; Barron, 1980, pl. 5, fig. 5; Barron, 1985, fig. 11.2; Akiba, 1986, pl. 12, figs. 1, 3–4. (**Plate 3, Figs. 1–2**)
- Thalassiosira* sp. cf. *T. convexa* Mukhina, 1965: pp. 22–24, pl. 2, figs. 1–2. **Remarks:** Specimens resemble *T. convexa* but they differ to some extent from typical form by more flat valve, arrangement of areolae and character of the marginal zone. (**Plate 6, Figs. 11, 13–17; Plate 4, Fig. 15**)
- Thalassiosira decipiens* (Grunow) Jørgensen; Sancetta, 1982, pl. 5, figs. 1–3.
- Thalassiosira delicata* (Barron) Akiba, 1986: p. 440. **Synonym:** *Thalassiosira nidulus* var. *delicata* Barron, 1980: p. 671, pl. 6, figs. 1, 4.
- Thalassiosira dolmatovae* Oreshkina in Gladenkov et al., 1992: p. 129, pl. 40, figs. 7–8. **Synonym:** *Thalassiosira* sp. 9 of Dolmatova in Volobueva et al., 1992: p. 86, pl. 30, figs. 1–5. (**Plate 1, Fig. 1; Plate 3, Fig. 24**)
- Thalassiosira eccentrica* (Ehrenberg) Cleve; Makarova, 1988b, pl. 20, figs. 1–9; pl. 21, figs. 1–12; Makarova, 1988c, pl. 40, figs. 1–9. (**Plate 4, Fig. 14; Plate 6, Fig. 9**)
- Thalassiosira gravida* Cleve; Schrader and Fenner, 1976, pl. 16, figs. 5–6, pl. 17, fig. 2; Barron, 1980, pl. 6, figs. 11, 14; Akiba, 1986, pl. 10, figs. 1–4. **Remarks:** No separation of the species from *Thalassiosira gravida* f. *fossilis* Jousé (1961: p. 63, pl. 1, fig. 9) was done in the material studied. (**Plate 2, Fig. 6**)
- Thalassiosira hyalina* (Grunow) Gran; Sancetta, 1982, pl. 5, figs. 4–5; Akiba, 1986, pl. 5, fig. 9; Makarova, 1988b, pl. 45, figs. 1–10. (**Plate 3, Figs. 7–8, 18**)
- Thalassiosira jacksonii* Koizumi et Barron in Koizumi, 1980: p. 396, pl. 1, figs. 11–14; Barron, 1980, pl. 6, figs. 2, 6; Akiba, 1986, pl. 11, fig. 2. **Synonym:** *Thalassiosira* sp. b of Schrader and Fenner, 1976, pl. 17, figs. 5, 10. (**Plate 6, Figs. 7–8**)
- Thalassiosira* sp. cf. *T. jacksonii* Koizumi et Barron. **Remarks:** Specimens resemble *T. jacksonii* but differ from the latter by lacking a distinct central hyaline area with a process.
- Thalassiosira jouseae* Akiba, 1986: p. 440, pl. 6, figs. 8–10. (**Plate 1, Figs. 3, 7, 10**)
- Thalassiosira kryophilata* (Grunow) Jørgensen; Sheshukova-Poretskaya, 1967, pl. 14, fig. 6; Koizumi, 1973, pl. 8, fig. 3; Makarova, 1988b, pl. 35, fig. 3. (**Plate 2, Fig. 11**)
- Thalassiosira latimarginata* Makarova; Makarova, 1988b, pl. 30, figs. 1–12; Makarova, 1988c, pl. 40, figs. 11–17. **Synonym:** *Thalassiosira trifulta* Fryxell in Fryxell and Hasle, 1979: pp. 16–19, pls. 1–5, figs. 1–24; Sancetta, 1982, pl. 5, figs. 10–12, pl. 6, figs. 1–2; Akiba, 1986, pl. 10, figs. 5–7. (**Plate 1, Fig. 4; Plate 6, Fig. 1**)
- Thalassiosira leptopus* (Grunow) Hasle et Fryxell; Akiba, 1986, pl. 9, figs. 3–4; Makarova, 1988b, pp. 49–50; Makarova, 1988c, pl. 42, fig. 12. (**Plate 4, Fig. 17**)

- Thalassiosira lineata* Jousé, 1968: p. 13, pl. 1, figs. 1–2; Akiba, 1986, pl. 14, figs. 7, 9.
- Thalassiosira manifesta* Sheshukova, 1964; Sheshukova-Poretskaya, 1964, p. 72, pl. 1, figs. 6–7; 1967, pl. 14, figs. 9a–b; Akiba, 1986, pl. 9, figs. 1–3. (**Plate 7, Figs. 8, 10**)
- Thalassiosira marnjanica* Sheshukova emend. Makarova, 1988; Makarova, 1988b, pp. 51–52, pl. 24, figs. 1–13; 1988c, pl. 41, figs. 13–21. **Synonyms:** *Thalassiosira decipiens* (Grunow) Jørgensen sensu Sheshukova-Poretskaya, 1964, pl. 1, fig. 2; 1967, pl. 14, fig. 2; *Thalassiosira borealis* Koizumi, 1980: p. 395, pl. 1, figs. 7–10. (**Plate 3, Figs. 25, 27**)
- Thalassiosira nativa* Sheshukova, 1964; Sheshukova-Poretskaya, 1964, p. 75, pl. 1, figs. 4–5; 1967, pl. 14, figs. 7 a–c. (**Plate 1, Figs. 5–6**)
- Thalassiosira* sp. cf. *T. nativa* Sheshukova. **Remarks:** Small specimens resemble *T. nativa* having some indistinct characters for the precise identification were assigned to this category and tabulated together with specimens of *T. nativa*.
- Thalassiosira nidulus* (Tempère et Brun) Jousé; Akiba, 1986, pl. 6, figs. 5–7.
- Thalassiosira oestropii* (Ostenfeld) Proshkina-Lavrenko; Barron, 1980, pl. 5, fig. 4; Barron, 1985, figs. 11.5–11.6; Akiba, 1986, pl. 14, figs. 1–6; Makarova, 1988b, pl. 25, figs. 1–9; Makarova, 1988c, pl. 42, figs. 13–17. (**Plate 3, Figs. 11–12**)
- Thalalassiosira orientalis* Sheshukova emend. Makarova, 1988; Makarova, 1988b, p. 77, pl. 50, figs. 1–9; 1988c, pl. 52, figs. 13–17. **Synonyms:** *Thalalassiosira margaritae* (Frenguelli et Orlando) Kozlova sensu Sheshukova-Poretskaya, 1964, pl. 2, figs. 1–3; *Thalalassiosira* aff. *margaritae* (Frenguelli et Orlando) Kozlova sensu Sheshukova-Poretskaya, 1967, pl. 14, figs. 5a–c. (**Plate 7, Fig. 9**)
- Thalassiosira praeoestropii* Dumont et al., 1986 emend. Bodén, 1993: pp. 67–68, pl. 1, figs. H–J, pl. 2, figs. C–G, pl. 3, figs. H, J. (**Plate 7, Figs. 1–2**)
- Thalassiosira sheshukovae* Makarova, 1988; Makarova, 1988a, p. 1185, pl. 2, figs. 1–11. **Synonym:** *Pseudopodosira elegans* Sheshukova; Sheshukova-Poretskaya, 1964, p. 75–76, text fig. 3, pl. 2, figs. 4–5; 1967, pl. 24, fig. 3; Pl. 25, fig. 4; Sancetta, 1982, pl. 4, figs. 1–2; Akiba, 1986, pl. 4, figs. 5–7. (**Plate 1, Fig. 8**)
- Thalassiosira temperei* (Brun) Akiba et Yanagisawa, 1986: p. 493, pl. 31, figs. 1–7; Yanagisawa, 1990, pl. 1, figs. 16, 25. **Synonyms:** *Coscinodiscus temperei* Brun; Kanaya, 1959, pl. 4, fig. 8; Barron, 1980, pl. 4, fig. 5; Akiba et al., 1982, pl. 1, fig. 5; *Cymatotheca weissflogii* (Grunow) Hendey sensu Sheshukova-Poretskaya, 1967, pl. 26, fig. 1; sensu Hanna, 1970, figs. 15–16. (**Plate 3, Fig. 23**)
- Thalassiosira tertiaria* Sheshukova, 1967; Sheshukova-Poretskaya, 1967, p. 148, pl. 15, fig. 2.
- Thalassiosira undulosa* (Mann) Sheshukova, 1967; Sheshukova-Poretskaya, 1967, pp. 148–149, pl. 16, figs. 1 a–c; Koizumi, 1973, pl. 8, figs. 5–6; Akiba, 1986, pl. 9, fig. 4. **Synonym:** *Coscinodiscus undulosus* Mann; Hanna, 1970, fig. 3. (**Plate 4, Fig. 19**)
- Thalassiosira* Cleve spp. **Remarks:** The precise identification of *Thalassiosira* species having sublinear, tangential or fasciculated areolae pattern, with an indistinct structure of the marginal and central zones, was not attempted. These specimens were not tabulated separately in the occurrence table.
- Thalassiothrix longissima* Cleve et Grunow; Schrader, 1973, pl. 23, figs. 7, 17–18; Akiba, 1986, pl. 21, fig. 18.
- Thalassiothrix robusta* (Schrader) Akiba, 1986: p. 441, pl. 21, fig. 4. (**Plate 3, Figs. 5–6; Plate 4, Fig. 9**)
- Trochosira spinosa* Kitton; Sheshukova-Poretskaya, 1967, pl. 11, figs. 6a–b, pl. 13, figs. 4a–b. **Remarks:** See Remarks for *Hyalopyxis concava* (Sheshukova) Makarova.
- Xanthiopyxis globosa* Ehrenberg; Barron, 1975, pl. 15, figs. 8–9.
- Xanthiopyxis ovalis* Lohman, 1938: p. 91, pl. 20, fig. 6, pl. 22, fig. 12; Hanna, 1970, fig. 70; Barron, 1975, pl. 15, fig. 13.
- Xanthiopyxis* (Ehrenberg) Ehrenberg spp. **Remarks:** All scarce specimens not referable to *X. globosa* or *X. ovalis* were assigned to this category.

#### Silicoflagellates

- Distephanus crux* s. ampl. (Ehrenberg) Haeckel; Perch-Nielsen, 1985, figs. 18.7–18.10.
- Distephanus speculum pentagonum* Limmermann; Perch-Nielsen, 1985, fig. 20.1.
- Distephanus speculum speculum* (Ehrenberg) Glezer; Perch-Nielsen, 1985, figs. 20.8–20.9.

**PLATES 1-7**

## Plate 1

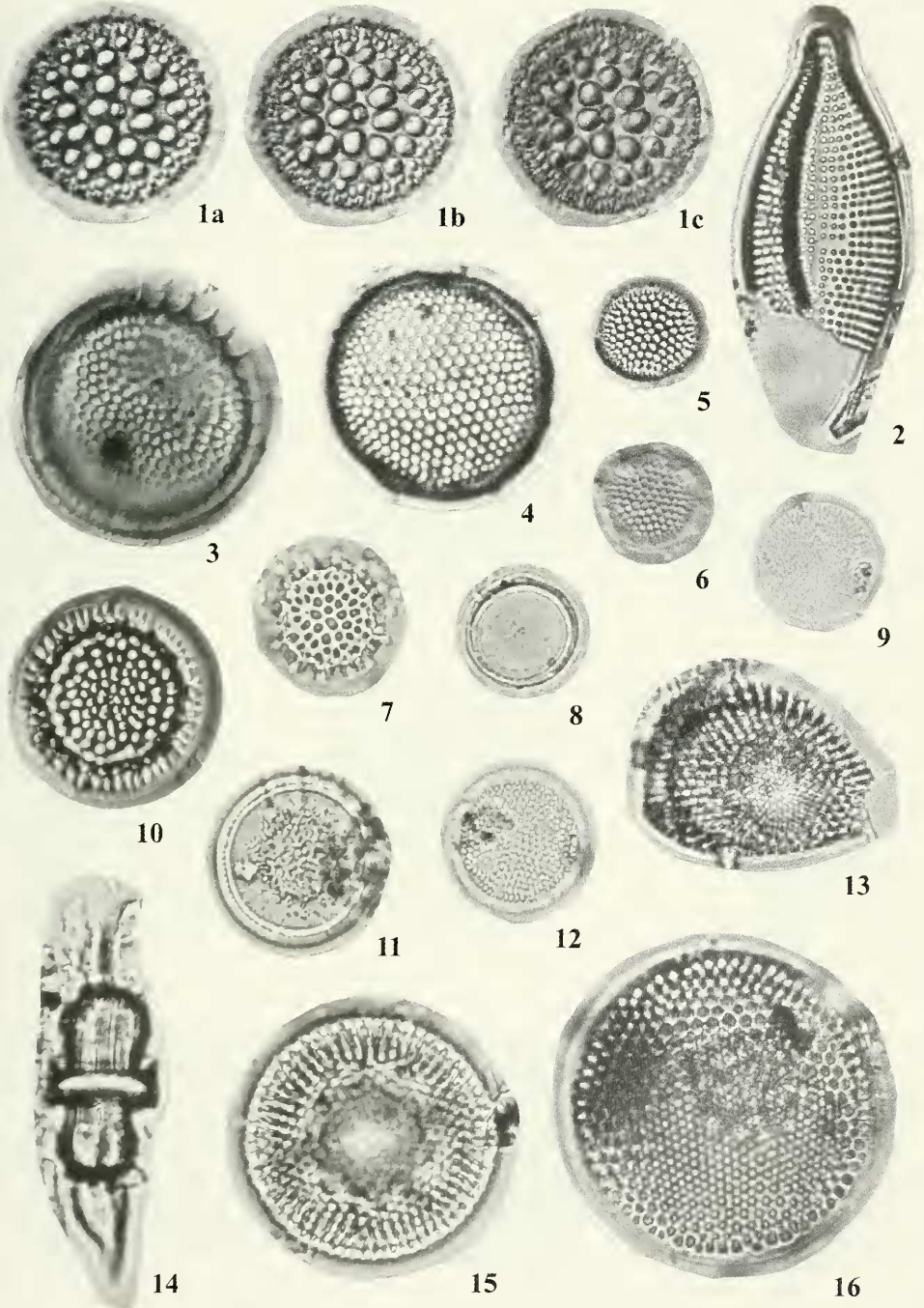
Fig. 1: *Thalassiosira dolmatovae* (a–c: valve in different focus). Fig. 2: *Adoneis pacifica*. Figs. 3, 7, 10: *Thalassiosira jouseae*. Fig. 4: *Thalassiosira latimarginata*. Figs. 5–6: *Thalassiosira nativa*. Fig. 8: *Thalassiosira sheshukovae*. Fig. 9: *Detonula confervacea*. Fig. 11: *Hyalodiscus obsoletus*. Fig. 12: *Actinocyclus* sp. Figs. 13, 15–16: *Pyxidicula zabelinae*. Fig. 14: *Stephanogonia hanzawae*.

Light microscope (LM). Magnification  $\times 1000$  except of Fig. 4 ( $\times 1250$ ).

Figs. 1–3, 7–9, 11–14: CAS 608382. Fig. 4: CAS 608426. Figs. 5, 10: CAS 617358. Fig. 6: CAS 608378. Fig. 15: CAS 608376. Fig. 16: CAS 608426.



PLATE 1



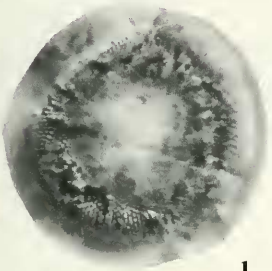
## Plate 2

Fig. 1: *Porosira punctata*. Figs. 2–3: *Dicladia capreolus*. Figs. 4–5: *Coscinodiscus marginatus*. Fig. 6: *Thalassiosira gravida*. Figs. 7, 10: *Odontella aurita*. Figs. 8–9: *Bacteriastrum varians*. Fig. 11: *Thalassiosira kryophila* (a–b: valve in different focus).

LM. Magnification  $\times 1000$ .

Fig. 1: CAS 608378. Figs. 2, 8: CAS 608400. Figs. 3, 5–7, 9–11: CAS 608382. Fig. 4: CAS 608397.

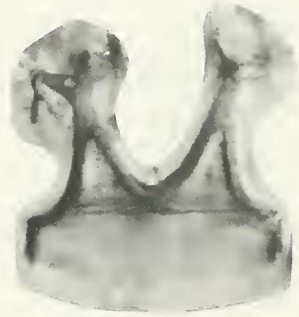
PLATE 2



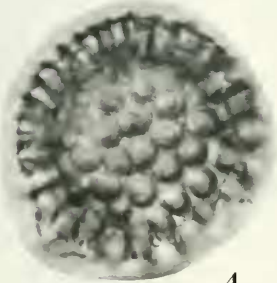
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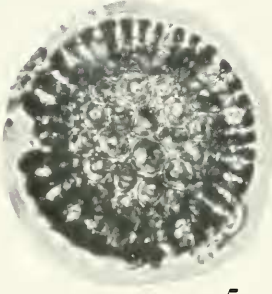
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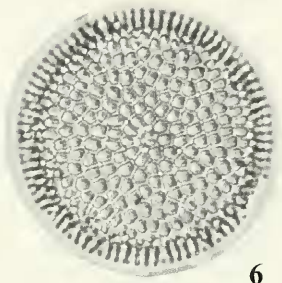
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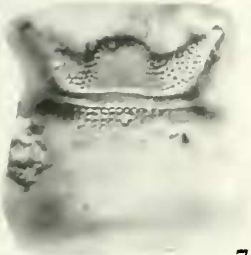
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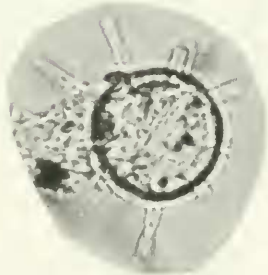
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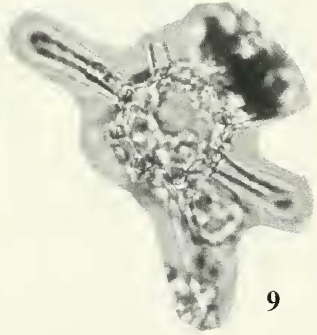
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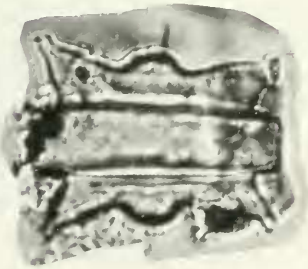
7



8



9



10



11a



11b

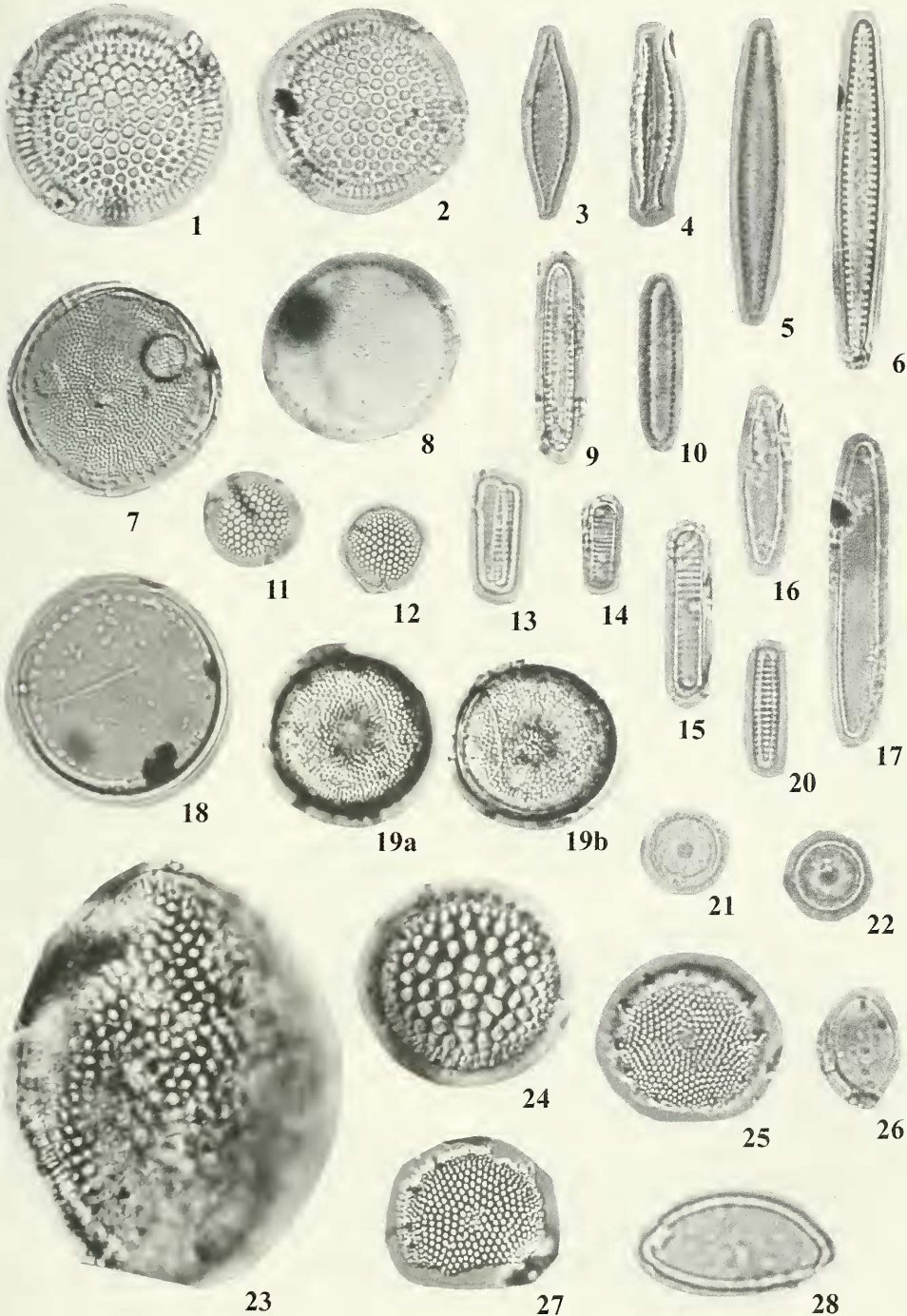
### Plate 3

Figs. 1–2: *Thalassiosira antiqua*. Figs. 3–4: *Cymatosira debyi*. Figs. 5–6: *Thalassiothrix robusta*. Figs. 7–8, 18: *Thalassiosira hyalina*. Figs. 9–10: *Thalassionema nitzschioides*. Figs. 11–12: *Thalassiosira oestrupii*. Fig. 13–15: *Fragilariopsis cylindrus*. Figs. 16–17: *Fragilariopsis oceanica*. Fig. 19: *Bacterosira fragilis* (a–b: valve in different focus). Fig. 20: *Nitzschia rolandii*. Figs. 21–22: *Hyalopyxis concava*. Fig. 23: *Thalassiosira temperei*. Fig. 24: *Thalassiosira dolmatovae*. Figs. 25, 27: *Thalassiosira marujamica*. Figs. 26, 28: *Chaetoceros* resting spores.

LM. Magnification  $\times 1000$  except of Figs. 11–12 ( $\times 600$ ).

Figs. 1, 6, 8, 10–11, 20, 23–24, 28: CAS 608382. Figs. 2, 18: CAS 60269–s. Figs. 3–4, 13–14, 19: CAS 608376. Figs. 5, 9: CAS 608424. Figs. 7, 12, 26: CAS 617358. Figs. 15–16: CAS 608393. Fig. 17: CAS 608376. Figs. 21–22, 25, 27: CAS 608371.

PLATE 3



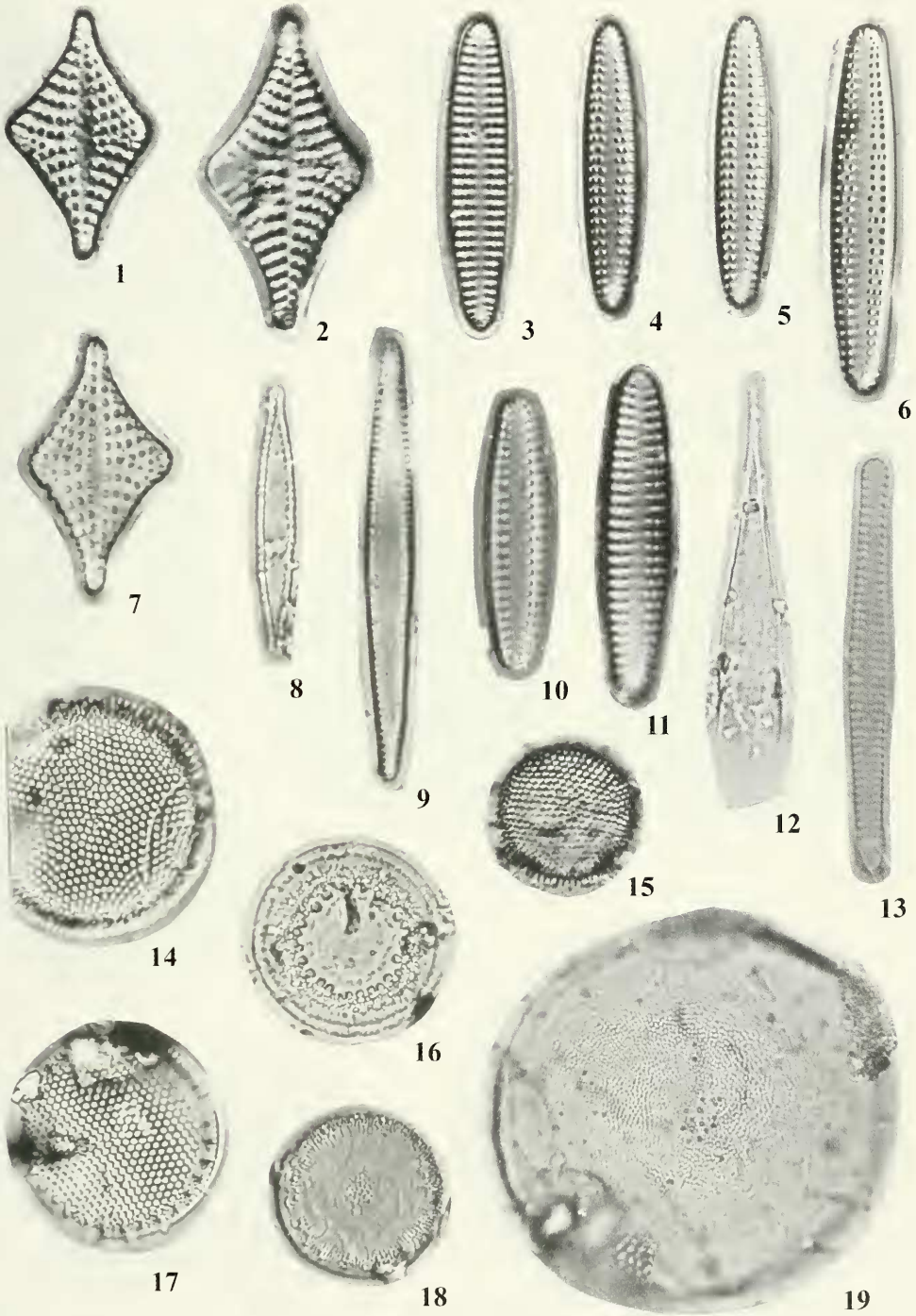
## Plate 4

Figs. 1–2, 7: *Rhaphoneis angularis*. Figs. 3–6, 10–11: *Delphineis angustata* group. Fig. 8: *Cymatosira debyi*. Fig. 9: *Thalassiothrix robusta*. Fig. 12: *Rhizosolenia hebetata* group. Fig. 13: *Delphineis sachalinensis*. Fig. 14: *Thalassiosira eccentrica*. Fig. 15: *Thalassiosira* sp. cf. *T. convexa*. Fig. 16: *Cosmiodiscus insignis*. Fig. 17: *Thalassiosira leptopus*. Fig. 18: *Bacterosira fragilis*. Fig. 19: *Thalassiosira undulosa*.

LM. Magnification  $\times 1000$ .

Figs. 1–2: CAS 617358. Figs. 3–6: CAS 608379. Figs. 7, 9–13, 16: CAS 608382. Figs. 14, 8, 19: CAS 608376. Fig. 15: CAS 608378. Fig. 17: CAS 608370. Fig. 18: CAS 608371.

PLATE 4



## Plate 5

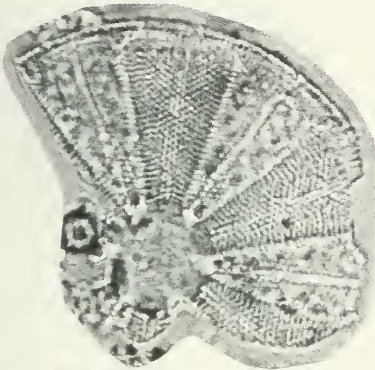
Fig. 1: *Actinoptychus splendens*. Figs. 2–4: *Neodenticula kantschatica*. Fig. 5: *Actinocyclus octonarius*. Figs. 6–7: *Delphineis simonsenii*. Fig. 8: *Actinoptychus senarius* (a–b: valve in different focus). Fig. 9: *Actinocyclus ochotensis*. Fig. 10: *Detonula confervacea*. Fig. 11–12: *Actinocyclus curvatulus*.

LM. Magnification  $\times 1000$ .

Figs. 1, 3–4, 6–7, 9, 12: CAS 608382. Fig. 2: CAS 608376. Fig. 5: CAS 608400. Fig. 8: CAS 608378. Fig. 10: CAS 617358. Fig. 11: CAS 608392.



PLATE 5



1



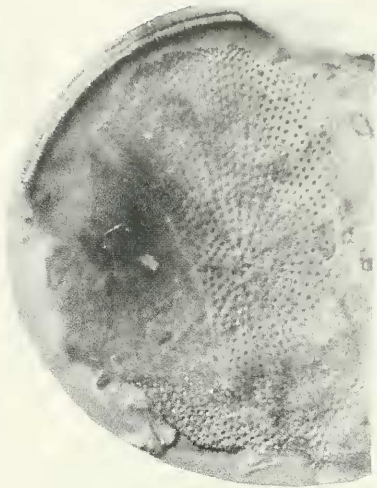
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3



4



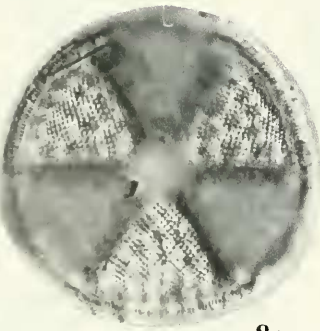
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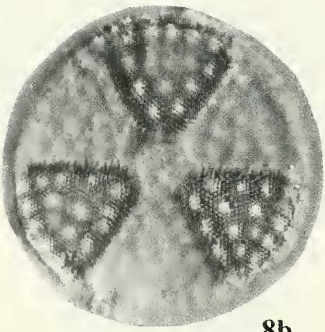
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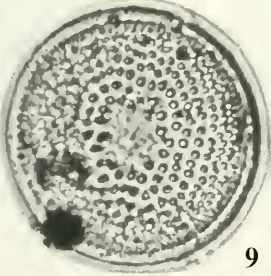
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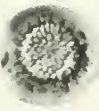
8a



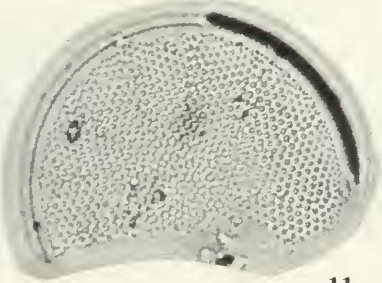
8b



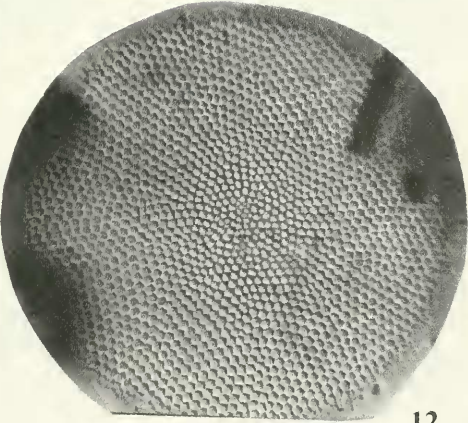
9



10



11



12

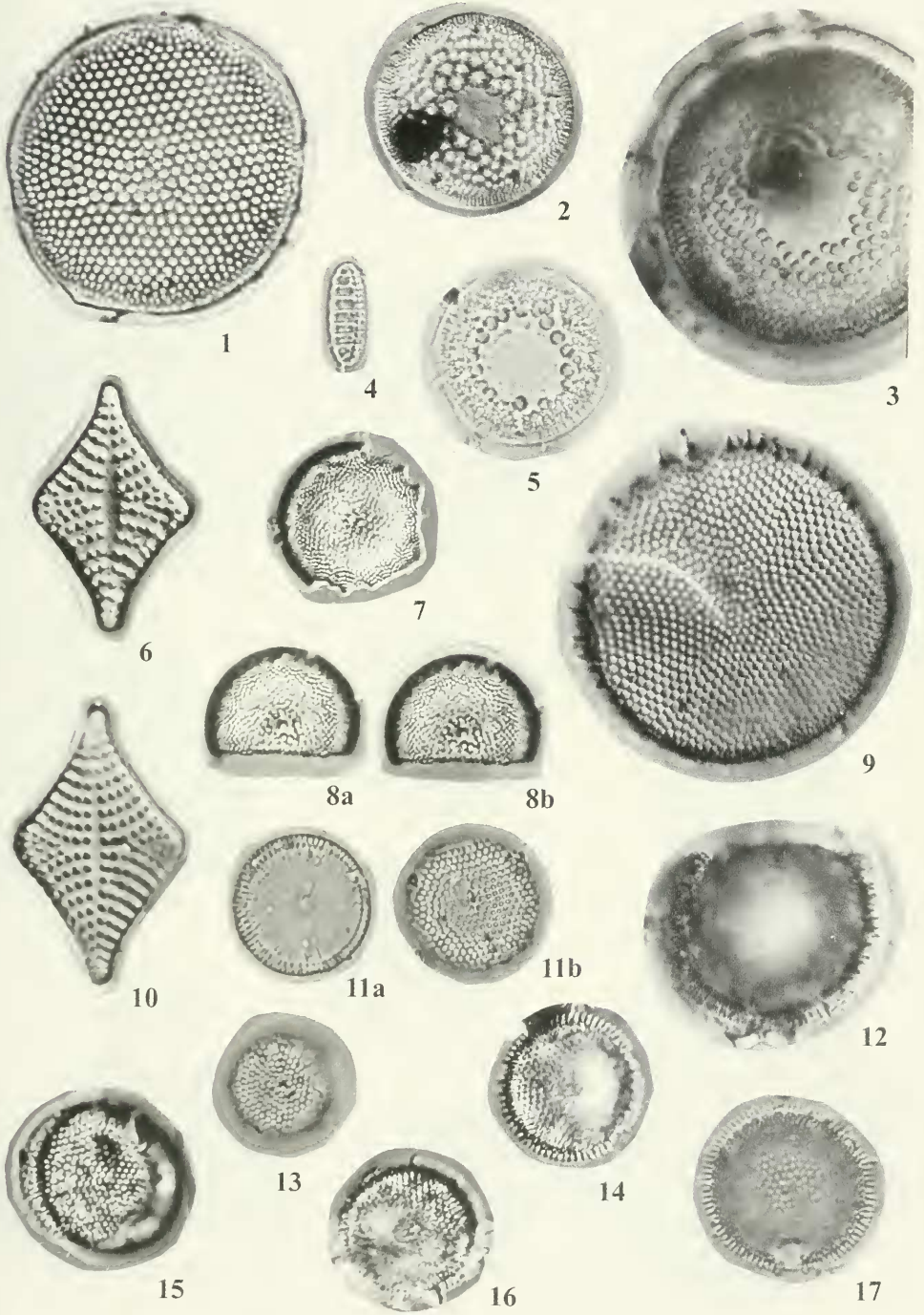
## Plate 6

Fig. 1: *Thalassiosira latimarginata*. Figs. 2–3, 5: *Cosmiodiscus insignis*. Fig. 4: *Neodenticula kamtschatica*. Figs. 6, 10: *Rhaphoneis angularis*. Figs. 7–8: *Thalassiosira jacksonii* (a–b: valve in different focus). Fig. 9: *Thalassiosira eccentrica*. Figs. 11, 13–17: *Thalassiosira* sp. cf. *T. convexa* (a–b: valve in different focus). Fig. 12: *Porosira punctata*.

LM. Magnification  $\times 1000$ .

Figs. 1: CAS 608408. Figs. 2, 6: CAS 617358. Figs. 3, 5, 9, 11: CAS 608382. Figs. 4, 7–8, 14–17: CAS 608376. Fig. 10: CAS 608379. Fig. 12: CAS 608378. Fig. 13: CAS 60269–s.

PLATE 6



## Plate 7

Figs. 1–2: *Thalassiosira praeoestrupii*. Figs. 3, 6: *Cladogramma dubium*. Fig. 4: *Pseudopyxilla americana*. Fig. 5: *Porosira glacialis* (a–b: valve in different focus). Figs. 7, 11: *Lithodesmium minusculum*. Figs. 8, 10: *Thalassiosira manifesta*. Fig. 9: *Thalassiosira orientalis*. Figs. 12–13: *Paralia sulcata*.

LM. Magnification  $\times 1000$ .

Figs. 1–2: CAS 60269–s. Figs. 3–4, 8–9, 11–12: CAS 608382. Figs. 5, 7: CAS 608376. Fig. 6: CAS 608408. Fig. 10: CAS 617358. Fig. 13: CAS 608392.

PLATE 7

